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Estimates of Fermilab Tevatron Collider Performance

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1. Introduction

This paper describes a model which has been used to estimate the average luminosity performance of the Tevatron collider. In the model, the average luminosity is related quantitatively to various performance parameters of the Fermilab Tevatron collider complex. The model is useful in allowing estimates to be developed for the improvements in average collider luminosity to be expected from changes in the fundamental performance parameters as a result of upgrades to various parts of the accelerator complex.

2. Definitions

Table 1 presents the definitions of the parameters used in this model.

Table 1: Parameter definitions and units

Parameter	Description	Units
B	Number of bunches in the collider	
ε_T	95% invariant transverse proton emittance at Tevatron low-beta (assumed equal in both planes)	π mm-mrad
$\bar{\varepsilon}_T$	95% invariant transverse antiproton emittance at Tevatron low-beta (assumed equal in both planes)	π mm-mrad
ε_T^a	Average 95% invariant transverse beam emittance at Tevatron low-beta (assumed equal in both planes)	π mm-mrad
τ	Luminosity lifetime	hours
β^*	beta-function at the Tevatron IP at full energy	m
n_T	Number of protons/bunch at Tevatron low-beta	10^{10}
$\bar{N}_T$	Total number of antiprotons at Tevatron low-beta	10^{10}

Y	Antiproton yield: antiprotons stacked into the Accumulator core per 120 GeV proton on the antiproton production target	10^{-6}
P	Number of 120 GeV protons on the antiproton production target per Main Ring cycle	10^{12}
C	Rate of Main Ring targeting cycles/sec	Hz
$\overline{N}_A$	Number of antiprotons in the Accumulator core	10^{10}
$\overline{N}_A^{max}$	Maximum number of antiprotons in the Accumulator core	10^{10}
R	Antiproton stacking rate	10^{10}/hr
$\overline{\varepsilon}_A$	95% invariant transverse antiproton emittance at the Accumulator core (assumed equal in both planes)	π mm-mrad
ε_B	95% invariant transverse proton emittance from the Booster (assumed equal in both planes)	π mm-mrad
$\Delta\varepsilon$	Increase in the 95% invariant transverse proton emittance from the Booster to Tevatron low-beta (assumed equal in both planes)	π mm-mrad
$\Delta\overline{\varepsilon}$	Increase in the 95% invariant transverse antiproton emittance during transfer from the Accumulator core to Tevatron low-beta (assumed equal in both planes)	π mm-mrad
t	time in the collider cycle	hr
T_s	Setup time	hr
T_q	Quiet time	hr
T	Stacking time	hr
$\mathcal{L}_0$	Initial luminosity	10^{30}/cm^2/sec
$\mathcal{L}_a$	Average luminosity	pb^{-1}/week
r	Efficiency of antiproton transfer, Accumulator core to Tevatron-low-beta	%
r_A	Efficiency of antiproton transfer, Accumulator core to Main Ring	%
r_M	Efficiency of antiproton transfer, Main Ring to Tevatron, 150 GeV	%
r_T	Efficiency of antiproton transfer, Tevatron, 150 GeV to Tevatron-low-beta	%
f	Unstacking fraction	%
f_{rev}	Tevatron beam revolution frequency	Hz

s_{bl}	Luminosity finite-bunch-length correction factor	%
g_l	Tevatron Collider operational efficiency	%
g_s	Antiproton Source stacking efficiency	%
$\rho(\kappa)$	Antiproton longitudinal density in the Accumulator core	10^{10}/eV-sec
κ	Antiproton longitudinal emittance in the Accumulator core	eV-sec
σ_κ	rms antiproton longitudinal emittance in the Accumulator core	eV-sec
κ_B	Antiproton longitudinal emittance unstacked per bunch	eV-sec
ρ_0	Peak antiproton longitudinal density in the Accumulator core	10^{10}/eV-sec
$\overline{N}_A^{unstack}$	Number of antiprotons unstacked from the Accumulator core	10^{10}
g_u	Unstacking efficiency	%
α_t	Intercept parameter describing 95% invariant antiproton transverse density vs. stack size dependence	π mm-mrad
β_t	Slope parameter describing 95% invariant antiproton transverse density vs. stack size dependence	π mm-mrad/10^{10}
γ_t	Quadratic parameter describing 95% invariant antiproton transverse density vs. stack size dependence	π mm-mrad/$(10^{10})^2$
α_l	Intercept parameter describing peak antiproton longitudinal density vs. stack size dependence	eV-sec
β_l	Slope parameter describing peak antiproton longitudinal density vs. stack size dependence	eV-sec/10^{10}
γ_l	Quadratic parameter describing peak antiproton longitudinal density vs. stack size dependence	eV-sec/$(10^{10})^2$
α_r	Intercept parameter describing antiproton transfer efficiency into the Main Ring vs. transverse emittance	%
β_r	Slope parameter describing antiproton transfer efficiency into the Main Ring vs. transverse emittance	%/π mm-mrad
γ_r	Quadratic parameter describing antiproton transfer efficiency into the Main Ring vs. transverse emittance	%/(π mm-mrad)^2

γ	Relativistic gamma at Tevatron IP	
F_t	Fraction of the Accumulator core lost transversely per hour	%/hr
F_l	Total number of antiprotons lost longitudinally from the Accumulator core per hour	10^{10}/hr
τ_{gas}	Accumulator core lifetime due to interactions with the residual gas	hr
<R>	"Operational" antiproton source stacking rate	10^{10}/hr
$<\mathcal{L}_a>$	"Operational" average luminosity	pb^{-1}/week

3. Model Relationships

3.1. General remarks

This model addresses only collider operation when cyclic equilibrium of the basic collider cycle has been attained. The model does not apply to transient situations in which one is starting operation from the $\overline{N}_A = 0$ situation. However, in the long run transient situations would not be expected to be important unless the mean time between stack losses of the antiproton source due to failures was comparable to or smaller than the cyclic equilibrium period $T+T_s+T_q$. This is not the case for the Fermilab antiproton source.

The cyclic equilibrium situation is represented in fig 1:

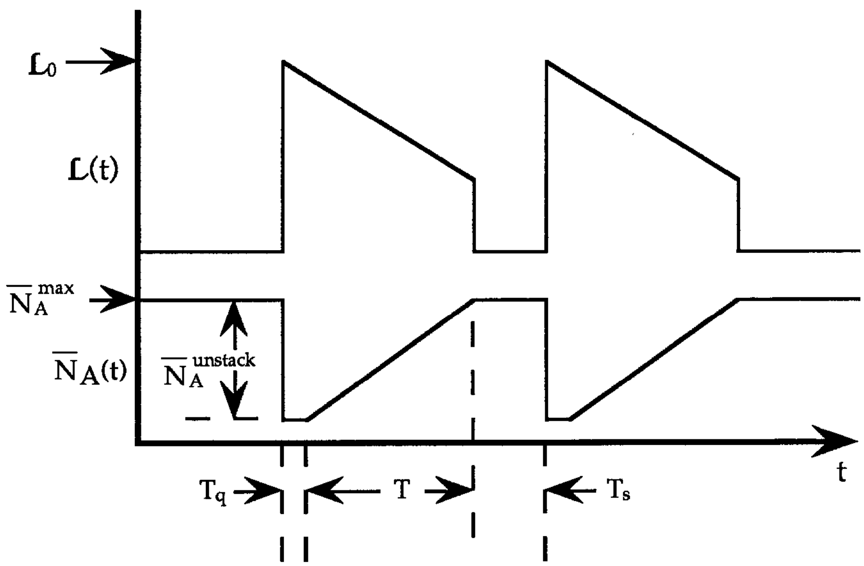


Figure 1: Cyclic equilibrium for collider operation

During the period T_s (the setup time), antiproton stacking does not occur, and preparations are made for loading the collider from the existing stack of $\overline{N}_A^{max}$ antiprotons. At the end of the setup time, the collider is loaded to an initial luminosity $\mathcal{L}_0$, with the removal from the Accumulator core of $\overline{N}_A^{unstack} = f\,\overline{N}_A^{max}$ antiprotons, where f (the unstacking fraction) is the fraction of the core removed. After a time T_q (quiet time: time to restore the antiproton source to the stacking mode), antiproton stacking resumes for a period of time T, after which the basic collider cycle repeats itself.

For the cyclic equilibrium situation shown in fig. 1, the average luminosity is given (in the units of Table 1) by

$$\mathcal{L}_a = [0.6048\,\mathcal{L}_0\,/(T_s+T_q+T)]\int_0^{T+T_q} \exp(-t/\tau)\,dt$$

$$= 0.6048\,\mathcal{L}_0\,\tau[1-\exp\{-(T+T_q)/\tau\}]/(T_s+T_q+T) \qquad (1)$$

assuming the luminosity lifetime is independent of time. This assumption is in fact not realized in the Tevatron collider, but will be made in this model for the sake of simplicity. The luminosity lifetime increases during a store, but not by more than a factor of two.

During the stacking time T, the Accumulator core must be restored to $\overline{N}_A^{max}$. Since the antiproton stacking rate $R = d\overline{N}_A/dt$ is in general a function of $\overline{N}_A$, the stacking time T is

$$T = \int_{(1-f)\overline{N}_A^{max}}^{\overline{N}_A^{max}} d\overline{N}_A/R(\overline{N}_A) \qquad (2)$$

Given an explicit parametric dependence of R on $\overline{N}_A$, equation 2 can be solved to give T as a function of f, $\overline{N}_A^{max}$, and the parameters of R; the result can be substituted into equation (1) to give the average luminosity as a function of f, $\overline{N}_A^{max}$, and the parameters of R. In addition (see 3.3, below), the initial luminosity $\mathcal{L}_0$ is a function of f, $\overline{N}_A^{max}$, and several other parameters.

3.2 Optimization of the average luminosity

With the actual form of $R(\overline{N}_A)$ and $\mathcal{L}_0$ as described in sections 3.3 and 3.4 below, the average luminosity $\mathcal{L}_a$ (and, of course, $\overline{N}_A^{max}$) increases with stacking time T to a maximum; after the maximum is reached, $\mathcal{L}_a$ decreases (although $\overline{N}_A^{max}$ continues to increase). The general form of this dependence is illustrated in fig. 2.

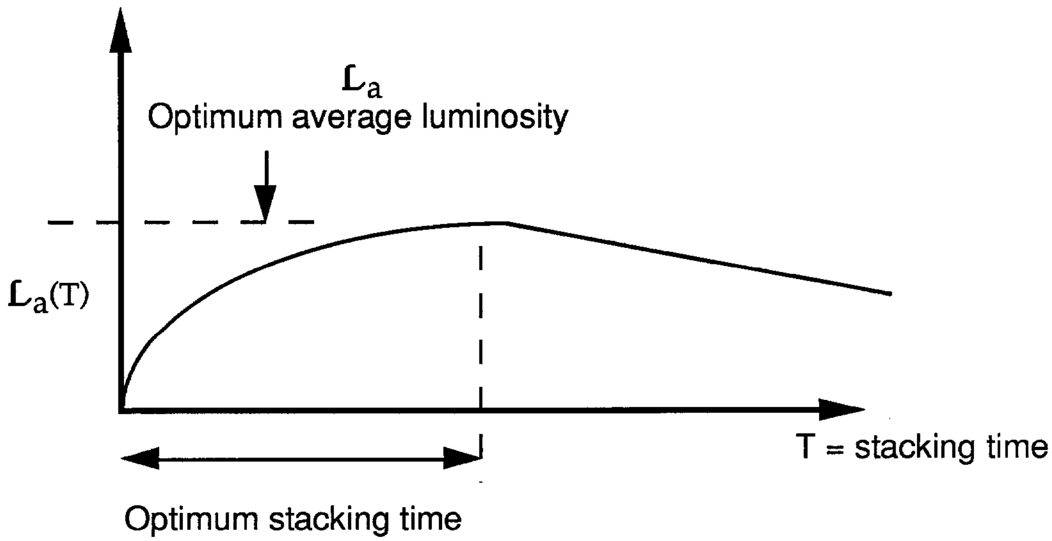


Figure 2: General behavior of the average luminosity as a function of the stacking time

The value of T at the maximum is the "optimum stacking time", and the corresponding value of $\overline{N}_A^{max}$ is the "optimum maximum stack". The optimum stacking time (plus T_q) is also the optimum storage time. Operation of the collider in the cyclic equilibrium mode with T equal to the optimum stacking time will maximize the average (and hence integrated) luminosity. The model calculation determines this optimum stacking time, optimum maximum stack and the corresponding value of the average luminosity, as a function of the other parameters in the model.

The full calculation computes T by numerical integration of equation (2) using the form of $R(\overline{N}_A)$ given below in section 3.4. However, it is useful to introduce a simplified approximation to $R(\overline{N}_A)$ in order to illustrate several features of the model. This simplified approximation is:

$$R(\overline{N}_A) = R \text{ for } \overline{N}_A \leq \overline{N}_A^{max},$$

$$R(\overline{N}_A) = 0 \text{ for } \overline{N}_A > \overline{N}_A^{max}, \qquad (3)$$

in which $\overline{N}_A^{max}$ is a fixed quantity, representing the maximum stack size which the Accumulator will tolerate; for stack sizes below this, the stacking rate is the constant R, independent of $\overline{N}_A$. Collider operation in cyclic equilibrium is assumed to consist of cycles in which one stacks in the Accumulator until $\overline{N}_A^{max}$ is reached, after which a transfer occurs.

In this approximation, the stacking time T is given by

$$T = \int_{(1-f)\overline{N}_A^{max}}^{\overline{N}_A^{max}} d\overline{N}_A / R(\overline{N}_A) = f\overline{N}_A^{max}/R \tag{4}$$

so that

$$\mathcal{L}_a = \mathcal{L}_0\, \tau\{1-\exp[-(f\overline{N}_A^{max}/R+T_q)/\tau]\}/(T_s+T_q+f\overline{N}_A^{max}/R) \tag{5}$$

If T_s and T_q are small compared to T, then this simplifies to

$$\mathcal{L}_a = \mathcal{L}_0\, R\tau[1-\exp(-f\overline{N}_A^{max}/R\tau)]/f\overline{N}_A^{max} \tag{6}$$

As discussed in section 3.3 below,

$$\mathcal{L}_0 \propto \overline{N}_T, \text{ and } \overline{N}_T \propto f\, \overline{N}_A^{max} ;$$

thus,

$$\mathcal{L}_a \propto R\tau[1-\exp(-f\overline{N}_A^{max}/R\tau)] \tag{7}$$

Two simple relations may be derived from this. The average luminosity may be written in terms of the parameter $x = f\overline{N}_A^{max}/R\tau$, as

$$\mathcal{L}_a \propto f\overline{N}_A^{max}[1-\exp(-x)]/x \tag{8}$$

The parameter x is just the ratio of the time required to replenish the stack to the luminosity lifetime. This parameter is small if the luminosity lifetime is large compared to the time required to replenish the stack; this may result from a large stacking rate or a small stack maximum. In this situation, we have

$$\mathcal{L}_a \propto f\overline{N}_A^{max} \tag{9}$$

The average luminosity is independent of the stacking rate or the luminosity lifetime; it is limited by the stack maximum, and also depends directly on the unstacking fraction.

The parameter x is large if the luminosity lifetime is small compared to the time required to replenish the stack; this may result from a small stacking rate, or a small luminosity lifetime, together with a large stack maximum. In this case, we have that

$$\mathcal{L}_a \propto R\tau \tag{10}$$

The average luminosity is independent of the stack maximum and depends only on the product of the stacking rate and the luminosity lifetime. This situation may also result if the mean time between failures of the collider becomes small, since the role of the mean time between failures is essentially equivalent to that of the luminosity lifetime.

3.3 *Initial luminosity*

The initial luminosity $\mathcal{L}_0$, using the units indicated above for all quantities, is given by:

$$\mathcal{L}_0 = 6 \times 10^{-8}\, n_T \overline{N}_T \gamma f_{rev}\, s_{bl} / 4\pi \beta^* \varepsilon_T^a$$

$$= 0.1616\, n_T \overline{N}_T / \beta^* \varepsilon_T^a, \tag{11}$$

using $f_{rev} = 47700$ Hz, $\gamma = 959$ (for 900 GeV operation), and $s_{bl} = 0.74$ (appropriate for $\beta^* = 0.5$ m and a longitudinal rms bunch length of about 0.4 m, which is roughly the case for all conditions studied with this model).

In this equation, we have

$$\varepsilon_T^a = (\varepsilon_T + \overline{\varepsilon}_T)/2, \text{ and} \tag{12}$$

$$\overline{\varepsilon}_T = \overline{\varepsilon}_A + \Delta\overline{\varepsilon}, \text{ and } \varepsilon_T = \varepsilon_B + \Delta\varepsilon \tag{13}$$

Equation 13 expresses the emittance dilution which may occur to the antiprotons during antiproton transfer, and to the protons during transfer from the Booster to the Tevatron. $\overline{\varepsilon}_A$ depends on $\overline{N}_A^{max}$, as described below. In this model, the proton transverse emittance ε_B is fixed at 15 π mm-mrad, and $\Delta\varepsilon$ is a parameter of the model.

We also have

$$\overline{N}_T = f\, \overline{N}_A^{max}\, r \tag{14}$$

where

$$r = r_A\, r_M\, r_T \tag{15}$$

is the product of the three individual transfer efficiencies. The efficiency r_A is a function of $\bar{\varepsilon}_A$, because of aperture restrictions at Main Ring injection, and hence is also a function of $\overline{N}_A^{max}$ (see section 3.7 below). The efficiencies r_M and r_T are taken to be independent of $\overline{N}_A^{max}$. The unstacking fraction f is discussed below in section 3.5.

Combining equations 11 through 15, we have for the initial luminosity

$$\mathcal{L}_0 = 0.3232\, n_T\, f\, \overline{N}_A^{max} r_A(\overline{N}_A^{max})\, r_M\, r_T/\beta^* \,[\varepsilon_B + \Delta\varepsilon + \bar{\varepsilon}_A(\overline{N}_A^{max}) + \Delta\bar{\varepsilon}] \qquad (16)$$

3.4 Antiproton Source Stacking Rate

The antiproton stacking rate, using the units indicated above for all quantities, is given by:

$$R(\overline{N}_A) = d\overline{N}_A/dt = 0.36\, Y(\overline{N}_A)PC \qquad (17)$$

The dependence of the antiproton yield Y on the stack intensity $\overline{N}_A$ depends principally on the performance of the stack-tail and core cooling systems in the Accumulator, the size of the Accumulator aperture, and the quality of the Accumulator vacuum. In fact, the yield also depends on the cycle rate C, but this dependence has been ignored here, since it is not important for the dynamics of the model.

The calculation of the yield variation with $\overline{N}_A$ involves estimates of loss mechanisms from the Accumulator. There are fundamentally three ways in which particles may be lost from the core:

(1) Transverse losses: The core emittance is determined by the equilibrium between heating mechanisms (such as intrabeam scattering) and the core cooling systems. This equilibrium is such that the core transverse emittance grows (approximately linearly) with stack size. The actual dependence of $\bar{\varepsilon}_A$ on $\overline{N}_A$ is parameterized as a quadratic:

$$\bar{\varepsilon}_A(\overline{N}_A) = \alpha_t + \beta_t\overline{N}_A + \gamma_t\overline{N}_A^2 \qquad (18)$$

This parameterization has been taken from empirical data obtaining during the 1988-89 collider run.[1] It represents the antiproton beam emittance in the cooled core, just prior to antiproton transfer, with the stack-tail system off. The actual core emittance during stacking, which is what is relevant here, is somewhat larger (see below).

As the core transverse emittance grows, beam may be scraped by the edges of the finite Accumulator aperture and be lost. The total fraction of the core lost by this mechanism per hour is denoted F_t; it depends on $\overline{N}_A$ through $\overline{\varepsilon}_A$.

(2) Attenuation through interactions with the residual gas: this is an exponential loss with time constant τ_{gas}.

(3) Longitudinal losses: at sufficiently high input fluxes to the stack-tail system, beam may be lost longitudinally, a process which depends on the intensity in the stack-tail, which in turn depends on the core intensity. The total longitudinal loss per hour is denoted F_l; it depends not only on $\overline{N}_A$, but also on the bandwidth of the stack-tail cooling system.

These three loss mechanisms together imply that the total change in the intensity of the Accumulator core with time is

$$R = d\overline{N}_A/dt = 0.36\, Y_0\, PC - \overline{N}_A/\tau_{gas} - \overline{N}_A\, F_t(\overline{N}_A) - F_l(\overline{N}_A) \qquad (19)$$

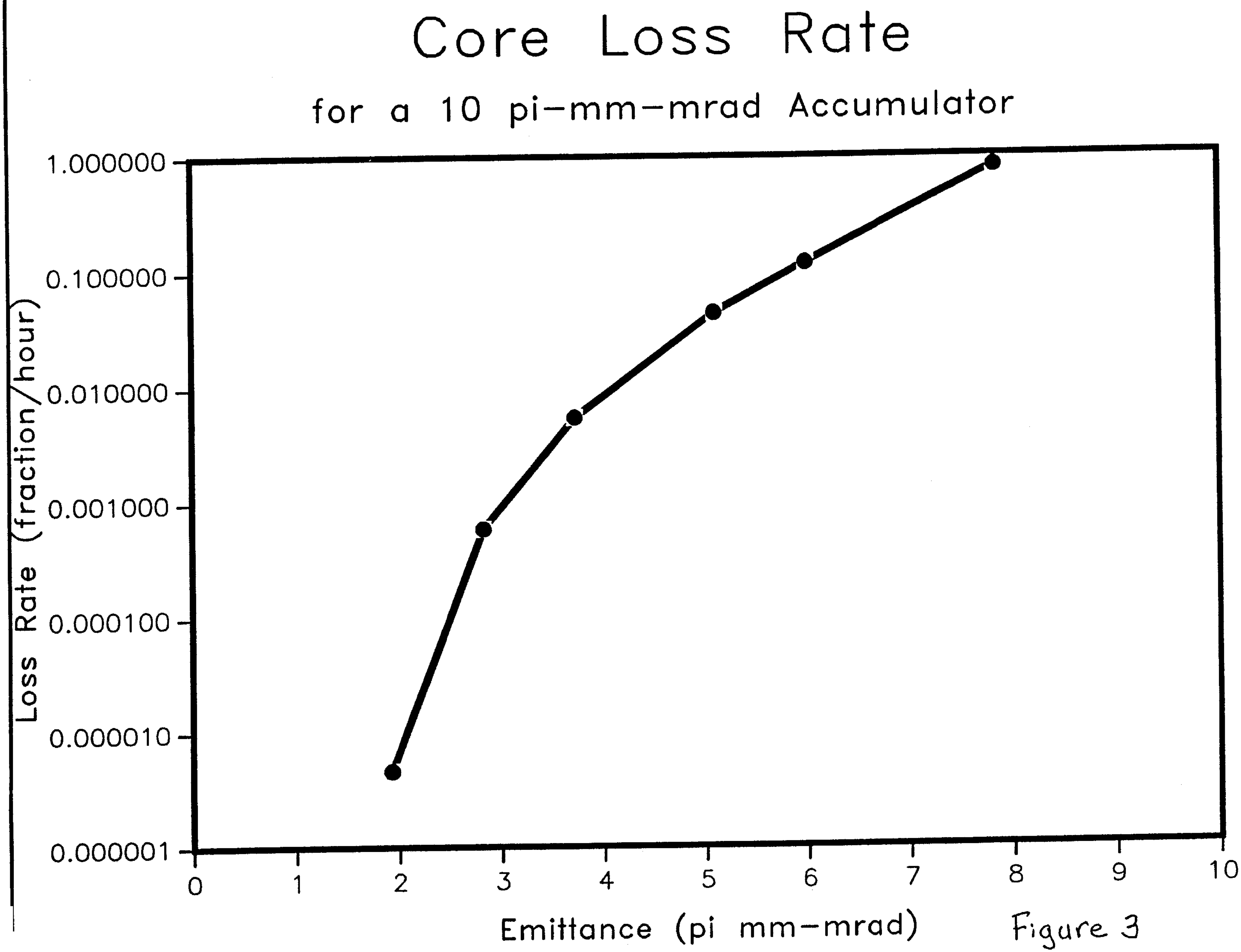
where $Y_0 = Y(0)$, the yield at $\overline{N}_A = 0$. The first term on the RHS in equation 19 represents the flux entering the core due to antiproton production. The last three terms represent the three loss mechanisms described above. Combining equations 17 and 19 gives,

$$Y(\overline{N}_A) = Y_0[1-\{\overline{N}_A[1/\tau_{gas}+F_t(\overline{N}_A)]+F_l(\overline{N}_A)\}/0.36PC] \qquad (20)$$

For the model calculation described in this paper, the function $F_t(\overline{\varepsilon}_A)$ has been computed numerically[2]; the result, for a 10 π mm-mrad aperture Accumulator, is shown in fig. 3. To obtain $F_t(\overline{N}_A)$, the transverse emittance $\overline{\varepsilon}_A$ has been related to $\overline{N}_A$ using equation 18, except that the emittance has been multiplied by a factor E to account for the fact that the core transverse emittance during stacking is actually larger than during antiproton transfer(which is what equation 18 expresses) since imperfections in the stack tail system heat the core beam transversely.

The function $F_l(\overline{N}_A)$ has also been computed numerically, from a computer simulation of the stochastic stacking process[2]. It depends on the parameters of the Accumulator stack tail system, particularly the system bandwidth, and on the momentum spread of the beam injected from the Debuncher.

Figs. 4 through 8 show the results of calculations of $Y(\overline{N}_A)$ vs $\overline{N}_A$, for various sets of conditions appropriate to different phases of the Fermilab III upgrade. Table 2 details the conditions associated with each of the figures.


Core Loss Rate
for a 10 pi-mm-mrad Accumulator
Loss Rate (fraction/hour)
1.000000
0.100000
0.010000
0.001000
0.000100
0.000010
0.000001
0
1
2
3
4
5
6
7
8
9
10
Emittance (pi mm-mrad)
Figure 3

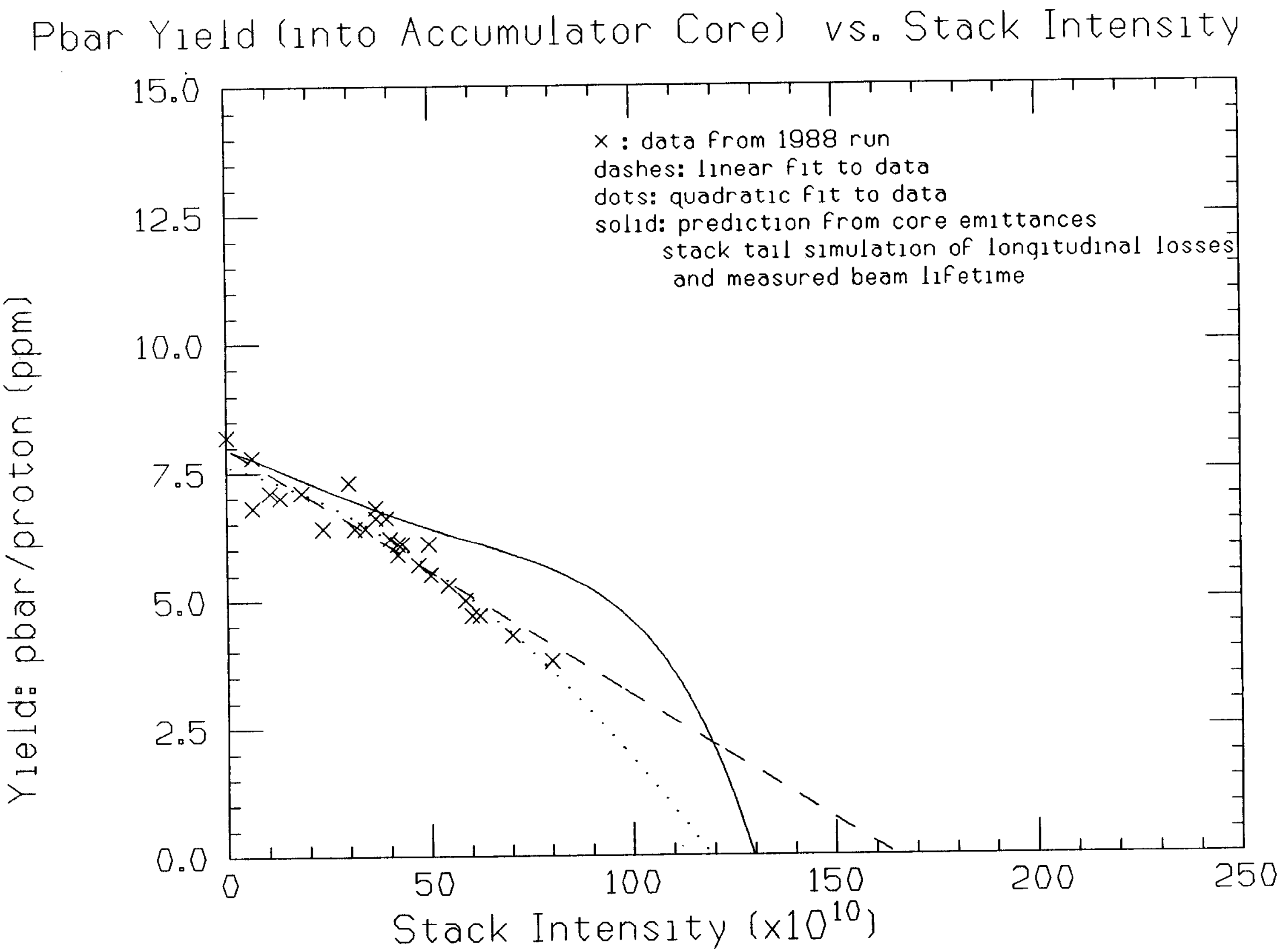

Pbar Yield (into Accumulator Core) vs. Stack Intensity
Yield: pbar/proton (ppm)
Stack Intensity (x10^10)
x : data from 1988 run
dashes: linear fit to data
dots: quadratic fit to data
solid: prediction from core emittances
stack tail simulation of longitudinal losses
and measured beam lifetime
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0
50
100
150
200
250

FIGURE 4

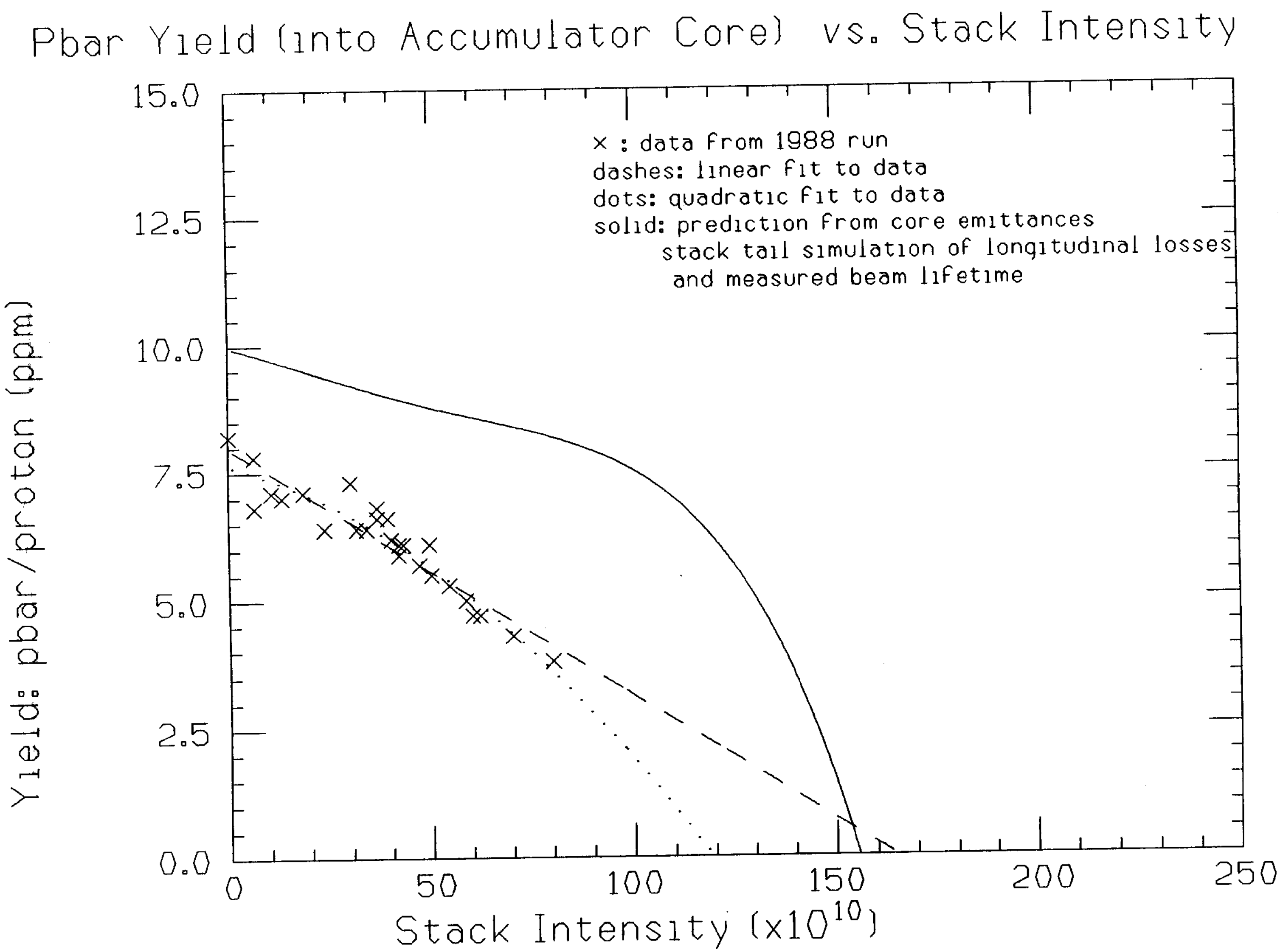

Pbar Yield (into Accumulator Core) vs. Stack Intensity
x : data from 1988 run
dashes: linear fit to data
dots: quadratic fit to data
solid: prediction from core emittances
stack tail simulation of longitudinal losses
and measured beam lifetime
Yield: pbar/proton (ppm)
Stack Intensity (x10^10)
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0
50
100
150
200
250

FIGURE 5

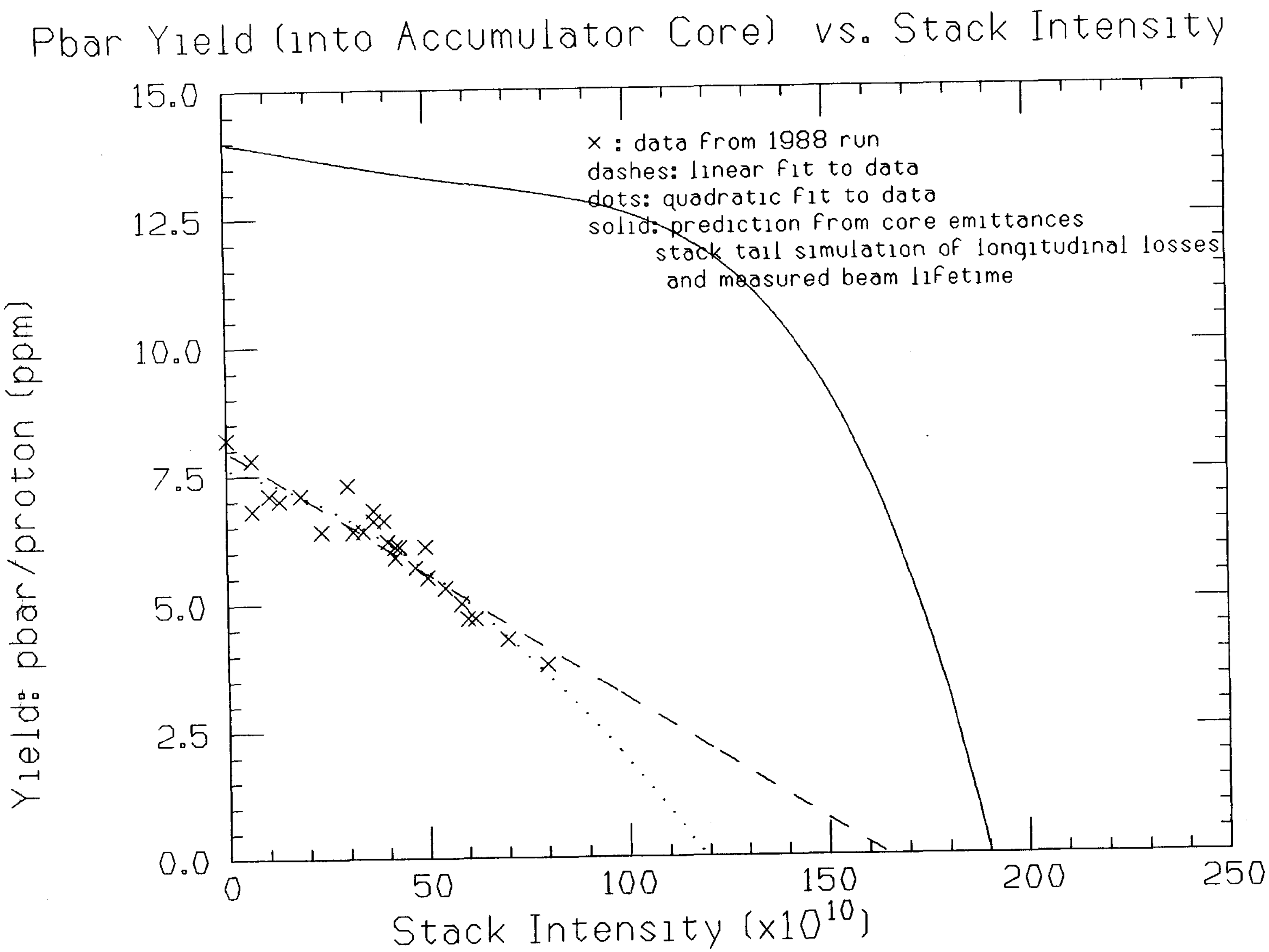
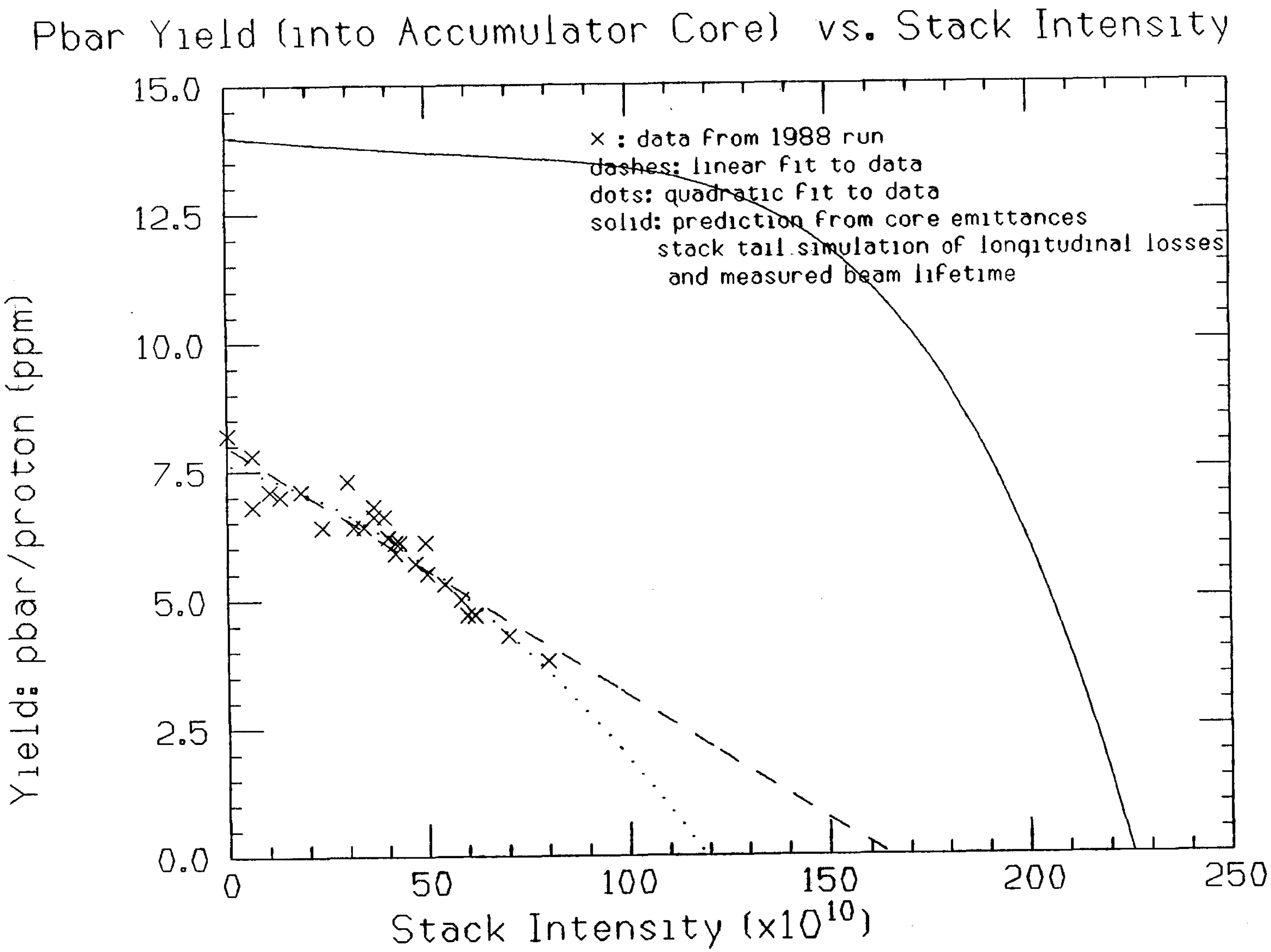

Pbar Yield (into Accumulator Core) vs. Stack Intensity
x : data from 1988 run
dashes: linear fit to data
dots: quadratic fit to data
solid: prediction from core emittances
stack tail simulation of longitudinal losses
and measured beam lifetime
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0
50
100
150
200
250
Yield: pbar/proton (ppm)
Stack Intensity (x10^10)

FIGURE 6



Pbar Yield (into Accumulator Core) vs. Stack Intensity
x : data from 1988 run
dashes: linear fit to data
dots: quadratic fit to data
solid: prediction from core emittances
stack tail simulation of longitudinal losses
and measured beam lifetime
Yield: pbar/proton (ppm)
Stack Intensity (x10^{10})
0.0
2.5
5.0
7.5
10.0
12.5
15.0
0
50
100
150
200
250

FIGURE 7

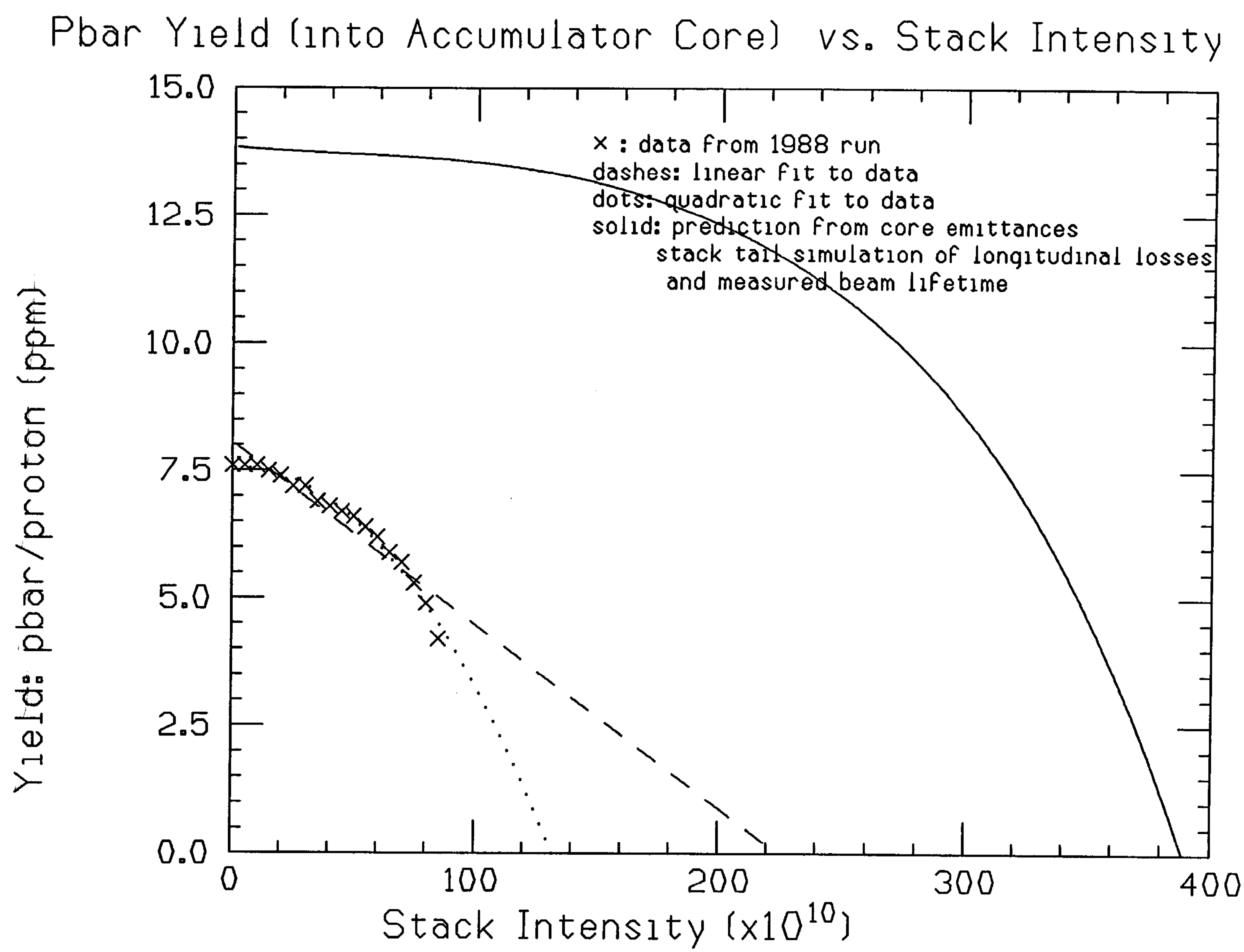
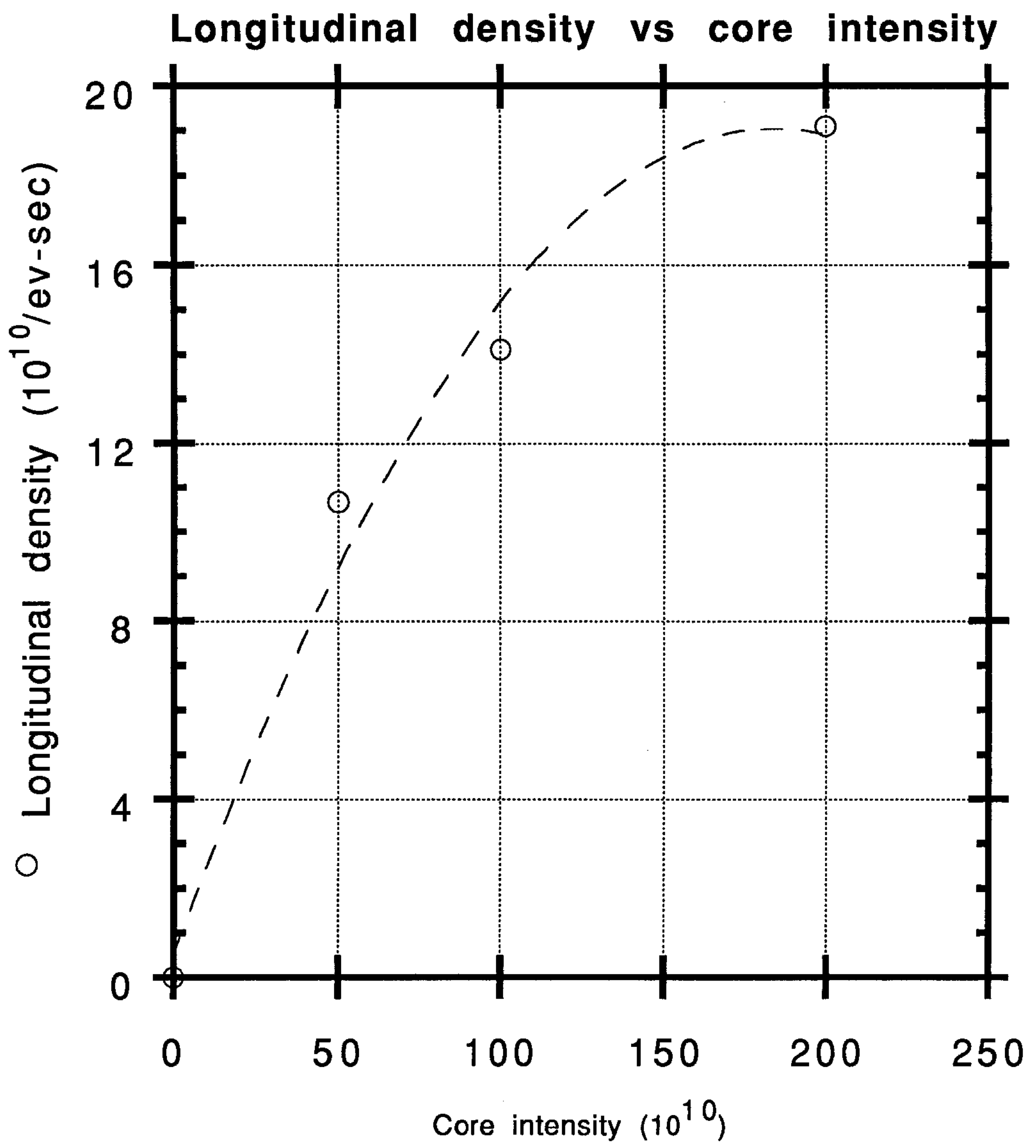

Pbar Yield (into Accumulator Core) vs. Stack Intensity
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0
100
200
300
400
Stack Intensity (x10^10)
Yield: pbar/proton (ppm)
× : data from 1988 run
dashes: linear fit to data
dots: quadratic fit to data
solid: prediction from core emittances
stack tail simulation of longitudinal losses
and measured beam lifetime

FIGURE 8



y = m0 + m1*x + m2*x^2 ... + m9*x^9
m0: 0.54381819638
m1: 0.20100182429
m2: -0.00054563638514
r: 0.99075134202

The data points are from
a calculation by J. Marriner,
which assumes 4-8 GHZ core cooling,
and which includes the effects of
intrabeam sacttering.

FIGURE 9

Table 2: List of parameters used for each of the curves shown in figs 4-8

Figure	C	P	Y_0	E	Stack-tail BW	Disk file
4	.384	1.7	7	3	1-2 GHz	LIMITS.STACK1
5	.5	1.7	10	1.5	1-2 GHz	LIMITS.STACK2
6	.5	3	14	1.5	1-2 GHz	LIMITS.STACK3
7	.667	5	14	1.5	1-2 GHz	LIMITS.STACK4
8	.667	5	14	1.5	2-4 GHz	LIMITS.STACK5

3.5 Antiproton Source Unstacking Fraction

The unstacking fraction, f, is calculated as follows. The Accumulator core is assumed to contain a total amount of beam $\overline{N}_A^{max}$, with a Gaussian distribution in longitudinal emittance κ:

$$d\overline{N}_A/d\kappa = \rho(\kappa) = \overline{N}_A^{max}\exp(-\kappa^2/2\sigma_\kappa^2)/\sqrt{(2\pi)}\,\sigma_\kappa \tag{21}$$

The peak longitudinal density, $\rho(0)$, is given by

$$\rho(0) = \overline{N}_A^{max}/\sqrt{(2\pi)}\sigma_\kappa = \rho_0 \tag{22}$$

In terms of this quantity, we can write

$$\rho(\kappa) = \rho_0 \exp(-\kappa^2\pi\rho_0^2/\overline{N}_A^{max}{}^2) \tag{23}$$

Unstacking proceeds as follows. For each of the B bunches, the unstacking process extracts a portion of the core (of longitudinal emittance κ_B) using an rf system, bunches this beam into roughly 10 53 MHz bunches (each of emittance $\kappa_B/10$), and injects it into the Main Ring for acceleration to 150 GeV. Because the beam must go through transition in the Main Ring, the longitudinal emittance per 53 MHz bunch cannot exceed roughly 0.1-0.15 eV-sec: this requires

$$\kappa_B/10 < .1\text{-}.15 \text{ ev-sec};$$

$$\kappa_B < 1\text{-}1.5 \text{ ev-sec}. \tag{24}$$

After acceleration in the Main Ring to 150 GeV, these 10 bunches are coalesced to form one 53 MHz bunch for injection into the Tevatron for collider operation. During the coalescing process, the total longitudinal emittance of the coalesced bunch grows to roughly 3-4 ev-sec, roughly independent of κ_B.

If the collider is operated with B bunches, then the total longitudinal emittance which must be removed from the Accumulator core is $\kappa_B B$. The amount of beam which corresponds to this emittance is

$$\overline{N}_A^{unstack} = \int_{-\kappa_B/2}^{\kappa_B/2} \rho(\kappa)d\kappa$$

$$= \overline{N}_A^{max}\, \mathrm{erf}\,(\kappa_B B\, \sqrt{\pi}\, \rho_0/2\overline{N}_A^{max}) \tag{25}$$

Thus, the unstacking fraction, $f = \overline{N}_A^{unstack}/\overline{N}_A^{max}$, is

$$f = g_u\, \mathrm{erf}\,(\kappa_B B\, \sqrt{\pi}\, \rho_0/2\overline{N}_A^{max}) \tag{26}$$

where g_u is an empirical de-rating factor which is inserted because the rf unstacking process is not completely efficient; typically $g_u = 0.75$.

If σ_κ is independent of $\overline{N}_A^{max}$, then ρ_0 is linear in $\overline{N}_A^{max}$ and f is independent of the stack size. In actual practice, the Accumulator core width σ_κ, which is determined by the equilibrium between the longitudinal core cooling systems and longitudinal heating mechanisms in the Accumulator, grows slowly with $\overline{N}_A$. The value of σ_κ also depends on the bandwidth of the core cooling systems, and is reduced with a 4-8 GHz system over that of the 2-4 GHz system present for the 1988-89 collider run. Fig. 9 shows the expected dependence of the core density ρ_0 on $\overline{N}_A$ with the new 4-8 GHz cooling system. Saturation of the density growth (increase in σ_κ with $\overline{N}_A$) is seen to occur at stacks in excess of $\overline{N}_A = 100$. The dependence of the peak longitudinal density ρ_0 on the stack size $\overline{N}_A$ is parameterized in the model as a quadratic:

$$\rho_0(\overline{N}_A) = \alpha_l + \beta_l\, \overline{N}_A + \gamma_l\, \overline{N}_A^2. \tag{27}$$

The values of the constants in equation (27) are determined either from empirical data[1] (for the 2-4 GHz cooling system used in the 1988-89 run) or from the information shown in fig. 9 (for the new 4-8 GHz system).

3.6 Antiproton Source Transverse Emittance.

The dependence of the antiproton source transverse emittance $\overline{\varepsilon}_A$ in the Accumulator on the stack size $\overline{N}_A$ results from the equilibrium between transverse stochastic cooling of the core, and transverse heating mechanisms such as intrabeam scattering. This dependence is determined empirically from data collected during the last collider run[1]; it is parameterized as a quadratic dependence, as given specifically in eq. 18. For the new 4-8 GHz core cooling system, the empirical parameters have been scaled appropriate to an increase in the transverse density by a factor of two, which is expected theoretically and is consistent with the observations (in the absence of ion effects).

3.7 Antiproton Transfer Efficiency

As discussed above in section 3.3, the antiproton transfer efficiency r is the product of three individual transfer efficiencies, as expressed in equation (7). The efficiency r_A depends on the antiproton transverse emittance $\bar{\varepsilon}_A$. The explicit dependence is expressed by the equation,

$$r_A(\bar{\varepsilon}_A) = \alpha_r + \beta_r\,\bar{\varepsilon}_A + \gamma_r\,\bar{\varepsilon}_A{}^2 \qquad (28)$$

The values of the constants in equation 28 have also been determined empircally[1]. Since $\bar{\varepsilon}_A$ depends on $\bar{N}_A$ through equation 18, r_A also depends on $\bar{N}_A$. The efficiencies r_M and r_T are taken as constants in this model.

3.8 Operational efficiency

In order to account for the downtime which is inevitable in complex systems, we define an "operational" average luminosity $<\mathcal{L}_a>$, and an "operational" antiproton source stacking rate $<R>$. These quantities are in general less than the quantities $\mathcal{L}_a$ and R, defined above in the model without operational considerations.

As a simple approximation to reality, we take the relations between the model's quantities and the operational quantities to be,

$$<\mathcal{L}_a> = g_l\,\mathcal{L}_a \qquad (29)$$

$$<R> = g_s\,R \qquad (30)$$

where g_l and g_s are fractions expressing the ratio of uptime to total scheduled time for the collider and antiproton source stacking systems respectively.

Although this sort of approach is appropriate for the antiproton source stacking system, in which downtime simply causes a net reduction in the average stacking rate, it is questionable whether it is correct for the collider. This is because a failure of the collider, in addition to introducing downtime for repair which diminishes the average luminosity, also has an impact due to the need to refill from the limited supply of antiprotons.

Hence, the reduction in the average luminosity may not simply be the ratio of collider downtime to total scheduled time. In order to provide a somewhat better estimate, the following hypothesis is made:

Consider M stores, with each store labelled by an index j, where j runs from 1 to M. A fraction η of the M collider stores are not characterized by failure; these ηM stores are terminated after the optimum store time T, as computed in the model described above. The storage time of each of these "good" stores is $T_j^{store} = T$.

The remaining $(1-\eta)M = M_{fail}$ stores "fail": that is, they terminate after a time T^{fail}, where T_j^{fail}, the failure time of the jth store, is chosen randomly from a probability distribution

$$dP/dT_j^{fail} \propto \exp(-T_j^{fail}/\overline{T^{fail}}) \qquad (32)$$

The storage time of the jth "bad" store is $T_j^{store} = T_j^{fail}$. After each "bad" store fails, there is a period T_{down} during which the collider is inoperative because of necessary repairs; stacking is also assumed to cease during this time.

Each of the M stores contributes an integrated luminosity,

$$\mathcal{L}_{Ij} = \mathcal{L}_{0\,j}\tau(1- \exp(-(T_j^{store}+T_q)/\tau) \qquad (33)$$

where $\mathcal{L}_{0\,j}$ depends on the stack size at the beginning of the store, and the stack accumulates during the store duration T_j^{store}. After the store ends, stacking ceases and there is a period of time equal to either T_s (for a "good" store) or T_s+T_{down} (for a "bad" store) before the next store starts. Stacking is off during this period.

The total amount of time associated with these M stores is

$$MT_{avg}^{store} = M(T_s+T_q)+\eta MT+(1-\eta)M(\overline{T^{fail}}+T_{down}) \qquad (34)$$

The "operational" average luminosity is then

$$<\mathcal{L}_a> = \sum_{j=1}^{M} \mathcal{L}_{Ij}/MT_{avg}^{store} \qquad (35)$$

whereas the total fractional uptime is

$$g_l = 1-(1-\eta)T_{down}/T_{avg}^{store} \qquad (36).$$

It is clear that in this case the simple relation given in equation 29 does not hold. As is illustrated in the computer calculations exhibited in the appendix, typical values from the 1988-89 collider run ($\overline{T^{fail}}$ = 9.5 hr, T_{down} = 6 hrs, and η = 0.45) give $\langle L_a \rangle / L_a$ = 0.67 and g_l = 0.84 from equations 35 and 36, respectively. For all of the calculations to be discussed below, we have used equation 29, but we have taken g_l = 0.6.

4. Collider performance in the Upgrade

4.1 Computer programs

The above model has been implemented in two computer programs written in VAX FORTRAN. One program, called LIMITS, essentially performs the calculations discussed in section 3.4, and produces the curves shown in figs. 4-8 as numerical output. This output is stored in the disk files shown in Table 2. This information, together with the other parameters of the model discussed above, is input to the second program, called LUMIN. This program performs the optimization discussed in section 3.2, thereby determining the optimum average luminosity, stacking and storage time, and optimum maximum stack.

The optimization is performed for each of three values of the parameter κ_B. This is done because the actual choice of the value of κ_B is subject to the "soft" constraint indicated by equation 24. This constraint is related to longitudinal effects in the Main Ring, which are not included in the model. The results of the optimization are presented under the heading, "STACK FOR THE OPTIMUM TIME". For the central value of κ_B, the program also computes the log derivative of the average luminosity with respect to each of the model parameters, in order to estimate the sensitivity of the average luminosity to each of the model parameters.

The average luminosity and stacking rate computed by the model are the "operational" quantities as defined by equations 29 and 30. However, the program also uses a Monte Carlo simulation technique to go through the calculations expressed by equations 35 and 36, for comparison. This part of the output is labelled, "sim results".

As the last step, the program repeats the calculations of the optimized quantities using the simplified approach discussed in the latter part of section 3.2. This is labelled as "STACK TO NSMAX" in the program's output. Log derivatives of the average luminosity are also calculated in this case.

The format and meaning of the input and output parameters for the two programs is fully documented through comments imbedded in the FORTRAN.

4.2 Results

As an example, the programs have been run for several sets of parameters, corresponding to the current definitions of the various phases of the Fermilab III upgrade, from the 1988-89 collider run through operation with the Main Injector. The values used for the luminosity lifetime correspond to calculated values at the beginning of each store; the calculations include the effects of intrabeam scattering, residual gas attenuation, and attenuation due to interactions at the beam collision points. Table 3 summarizes the results.

The actual output from the computer program LUMIN is given in the appendix to this report. In this output, the values for all the parameters described in Table 1 are given, for each step in the upgrade, together with the results of the model calculations which are summarized in Table 3.

References

1. G. Dugan, V. Bharadwaj, *An Empirical Model for the Luminosity of the Fermilab Tevatron Collider*, in Proceedings of the 15th International Conference on High Energy Accelerators, Toyko, 1990

2. J. Marriner, Pbar Note 511

Table 3:
Collider Performance Parameters
in the Fermilab Upgrade

	1988-89 Run	1991-2 Run	1993 Run	1994-5 Run	1996 Run
Parameter					
CM energy (GeV)	1800	1800	1800	2000	2000
Number of bunches(maximum)	6	6	6	36	36
Protons/bunch(10^{10}) at low-β	7	7	10	10	33
Antiprotons/bunch (10^{10}) at low-β	3.1	6.1	6.9	1.8	3.5
Total antiprotons extracted from the core (10^{10})	28	50	60	102	145
Antiproton longitudinal emittance per bunch, extracted from the core (eV-sec)	1	1.25	1.25	.5	.5
Antiproton transmission efficiency (%)	65	74	70	63	87
Invariant transverse emittance (95%, π mm-mrad) at low-β: proton (antiproton)	25 (18)	15 (13)	15 (15)	15 (20)	30 (22)
Longitudinal emittance (95%, eV-sec) at low-β: proton (antiproton)	3 (3)	3 (3)	3 (3)	3 (3)	3 (3)
β^*(m)	.55	.5	.5	.5	.5
Antiproton stacking rate (10^{10}/hour)	1.8	3.2	5.4	7.6	16.8
Initial luminosity lifetime (hr)	35	17	15	22	16
Average stack before transfer(10^{10})	77	75	93	137	200
Optimum stacking time (hr)	25	20	14	18	12
Linear beam-beam tune shift(Antiprotons)	.025	.007	.010	.010	.016
Mean number of inelastic interactions per crossing	.3	1	1.5	.4	1.7
INITIAL LUMINOSITY (10^{30}/cm^2/sec)	1.7	5.7	8.8	13.1	57.1
AVERAGE LUMINOSITY (pb^{-1}/week, assuming 60% uptime)	0.41	1.1	1.8	2.9	12.2
INTEGRATED LUMINOSITY per year (pb^{-1})	21	57	94	151	630

Appendix: Output from the program LUMIN for each step in the upgrade

AVERAGE LUMINOSITY ESTIMATE

1988-9 RUN

date = 29-AUG-91 time = 17:34:53

number of bunches= 6 peak stacking rate (ma/hr)= 1.785
number of crossings= 12
beam energy = 900.000 GeV
vary longitudinal emittance per bunch by +/- 0.050ev-sec

unstacking efficiency= 0.750
MR 20 GeV to Tev 150 GeV efficiency= (%) 92.000

parameters for transfer efficiency, Acc to MR at 20 GeV
0.1190000E+03-0.4661000E+01 0.1050000E+00

parameters for pbar emittance vs. stack size
0.4030000E+01 0.1984000E+00-0.9140000E-03

parameters for pbar longitudinal density vs.
stack size
0.1640000E+00 0.1470000E+00-0.8020000E-03

stacking rate vs intensity:
PRESENT (1989) SITUATION

stack rate rolloff from a model
emittance scale factor= 3.000
stack rate into the Accumulator= 1.883 ma/hr
yield into the Accumulator= 8.013ppm
beam lifetime in model (hrs)= 300.000
table describing yield rolloff vs stack
entries= 250

stack	yield into the core									
1.000	7.929	7.899	7.869	7.838	7.807	7.775	7.743	7.710	7.677	7.644
11.000	7.611	7.577	7.543	7.509	7.475	7.440	7.406	7.372	7.337	7.303
21.000	7.269	7.235	7.201	7.167	7.133	7.100	7.067	7.034	7.001	6.969
31.000	6.937	6.905	6.873	6.842	6.811	6.781	6.750	6.721	6.691	6.662
41.000	6.633	6.605	6.577	6.549	6.522	6.494	6.468	6.441	6.415	6.389
51.000	6.364	6.338	6.313	6.288	6.263	6.239	6.214	6.190	6.166	6.141
61.000	6.117	6.093	6.069	6.044	6.020	5.995	5.970	5.945	5.919	5.893
71.000	5.867	5.840	5.812	5.784	5.756	5.726	5.696	5.664	5.632	5.599
81.000	5.565	5.529	5.492	5.454	5.414	5.373	5.329	5.285	5.238	5.189
91.000	5.138	5.085	5.029	4.972	4.911	4.848	4.781	4.712	4.640	4.564
101.000	4.485	4.402	4.315	4.225	4.130	4.032	3.928	3.821	3.708	3.590
111.000	3.468	3.340	3.206	3.067	2.921	2.770	2.612	2.448	2.277	2.099
121.000	1.914	1.721	1.521	1.312	1.096	0.871	0.638	0.396	0.144	0.000
131.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
141.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
151.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
161.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
171.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
181.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
191.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
201.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
211.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
221.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
231.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
241.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

new parameters:
quiet time(hrs) = 0.500

```
setup time(hrs)                                  =   2.50
luminosity lifetime(hrs)                         =   34.5
pbar yield into Accumulator (ppm)                =   7.63
protons on target per cycle(x10**12)             =   1.80
kilocycles per hour                              =   1.30
stacking efficiency                              =  0.850
protons per bunch at low beta (x10**10)          =   7.00
Tev inj to low beta transfer efficiency          =  0.950
low beta (m)                                     =  0.550
overall emittance dilution (p)                   =   10.0
overall emittance dilution (pbar)                =   4.00
operational efficiency                           =  0.600
longitudinal emittance per bunch                 =   1.00
stack maximum                                    =   50.0
```

STACK FOR THE OPTIMUM TIME

epslng/bunch	fraction	lumin/wk (pb)**-1	lumin(peak) 10**29	t stack hrs	stack size x10**10	dpbar(core) x10**10	pbar/bunch x10**10	emittance p mm-mrad	emittance pb mm-mrad	trans eff	bb del-nu
0.950	0.350	0.392	16.635	24.050	77.200	27.024	2.933	25.000	17.899	0.651	0.025
1.000	0.367	0.406	17.384	25.015	76.900	28.218	3.064	25.000	17.882	0.651	0.025
1.050	0.383	0.419	18.123	25.993	76.800	29.409	3.193	25.000	17.876	0.651	0.025

```
log derivatives of integrated luminosity
quiet time(hrs)                          =  0.500     log derivative = -0.461E-02
setup time(hrs)                          =   2.50     log derivative = -0.892E-01
luminosity lifetime(hrs)                 =   34.5     log derivative =  0.326
pbar yield into Accumulator (ppm)        =   7.63     log derivative =  0.000E+00
protons on target per cycle(x10**12)     =   1.80     log derivative =  0.000E+00
kilocycles per hour                      =   1.30     log derivative =  0.000E+00
stacking efficiency                      =  0.850     log derivative =  0.233
protons per bunch at low beta (x10**10)  =   7.00     log derivative =   1.00
Tev inj to low beta transfer efficiency  =  0.950     log derivative =   1.00
low beta (m)                             =  0.550     log derivative =  -1.01
overall emittance dilution (p)           =   10.0     log derivative = -0.233
overall emittance dilution (pbar)        =   4.00     log derivative = -0.933E-01
operational efficiency                   =  0.600     log derivative =   1.00
longitudinal emittance per bunch         =   1.00     log derivative =  0.677
stack maximum                            =   50.0     log derivative =  0.000E+00

sim results
For   100 stores
probability of a store failure =      0.550
Down time after a failure (hr) =      6.000
Mean time between failures (hr) =      9.500
Initial stack size (10**10) =     12.000
average luminoisity ( pb**-1/week) =     0.453
average stack size = (10**10)    46.406
average store duration (hr) =    16.612
fractional downtime =      0.159
fraction of time in storage =      0.712
```

STACK TO NSMAX

epslng/bunch	fraction	lumin/day (nb)**-1	lumin(peak) 10**29	t stack hrs	stack size x10**10	dpbar(core) x10**10	pbar/bunch x10**10	emittance p mm-mrad	emittance pb mm-mrad	trans eff	bb del-nu
0.950	0.427	0.371	14.672	14.055	50.000	21.329	2.452	25.000	15.665	0.690	0.025
1.000	0.444	0.385	15.288	14.644	50.000	22.224	2.555	25.000	15.665	0.690	0.025
1.050	0.462	0.399	15.882	15.213	50.000	23.088	2.654	25.000	15.665	0.690	0.025

```
log derivatives of integrated luminosity
quiet time(hrs)                          =  0.500     log derivative = -0.204E-02
setup time(hrs)                          =   2.50     log derivative = -0.142
```

luminosity lifetime(hrs)	=	34.5	log derivative =	0.205
pbar yield into Accumulator (ppm)	=	7.63	log derivative =	0.000E+00
protons on target per cycle(x10**12)	=	1.80	log derivative =	0.000E+00
kilocycles per hour	=	1.30	log derivative =	0.000E+00
stacking efficiency	=	0.850	log derivative =	0.615E-01
protons per bunch at low beta (x10**10)	=	7.00	log derivative =	1.00
Tev inj to low beta transfer efficiency	=	0.950	log derivative =	1.00
low beta (m)	=	0.550	log derivative =	-1.01
overall emittance dilution (p)	=	10.0	log derivative =	-0.246
overall emittance dilution (pbar)	=	4.00	log derivative =	-0.984E-01
operational efficiency	=	0.600	log derivative =	1.00
longitudinal emittance per bunch	=	1.00	log derivative =	0.745
stack maximum	=	50.0	log derivative =	0.368

AVERAGE LUMINOSITY ESTIMATE

1992 RUN (New low-beta, separators)

date = 29-AUG-91 time = 17:35:23

number of bunches= 6 peak stacking rate (ma/hr)= 3.240
number of crossings= 2
beam energy = 900.000 GeV
vary longitudinal emittance per bunch by +/- 0.050ev-sec

unstacking efficiency= 0.750
MR 20 GeV to Tev 150 GeV efficiency= (%) 92.000

parameters for transfer efficiency, Acc to MR at 20 GeV
0.1190000E+03-0.4661000E+01 0.1050000E+00

parameters for pbar emittance vs. stack size
0.2010000E+01 0.9920000E-01-0.1000000E-05

parameters for pbar longitudinal density vs.
stack size
0.5438000E+00 0.2010000E+00-0.5456000E-03

stacking rate vs intensity:
tevatron upgrade phase Ia

stack rate rolloff from a model
emittance scale factor= 1.500
stack rate into the Accumulator= 3.060 ma/hr
yield into the Accumulator= 10.000ppm
beam lifetime in model (hrs)= 300.000
table describing yield rolloff vs stack
entries= 250

stack	yield into the core									
1.000	9.945	9.922	9.899	9.876	9.852	9.827	9.802	9.777	9.752	9.726
11.000	9.700	9.674	9.648	9.622	9.596	9.569	9.543	9.517	9.490	9.464
21.000	9.437	9.411	9.385	9.359	9.333	9.308	9.282	9.257	9.232	9.207
31.000	9.182	9.157	9.133	9.109	9.086	9.062	9.039	9.016	8.993	8.971
41.000	8.949	8.927	8.905	8.884	8.863	8.842	8.822	8.801	8.781	8.761
51.000	8.742	8.722	8.703	8.684	8.665	8.646	8.628	8.609	8.591	8.572
61.000	8.554	8.536	8.518	8.499	8.481	8.462	8.444	8.425	8.406	8.387
71.000	8.368	8.349	8.329	8.309	8.288	8.267	8.246	8.224	8.201	8.178
81.000	8.155	8.131	8.106	8.080	8.053	8.026	7.998	7.969	7.938	7.907
91.000	7.875	7.841	7.807	7.770	7.733	7.694	7.654	7.612	7.569	7.524
101.000	7.478	7.429	7.379	7.327	7.272	7.216	7.158	7.097	7.034	6.969
111.000	6.902	6.832	6.759	6.683	6.605	6.524	6.441	6.354	6.264	6.171
121.000	6.075	5.975	5.872	5.766	5.655	5.542	5.424	5.303	5.177	5.047
131.000	4.914	4.776	4.633	4.486	4.335	4.179	4.018	3.852	3.681	3.505
141.000	3.324	3.138	2.946	2.749	2.545	2.336	2.122	1.901	1.674	1.441
151.000	1.201	0.955	0.703	0.443	0.177	0.000	0.000	0.000	0.000	0.000
161.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
171.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
181.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
191.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
201.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
211.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
221.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
231.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
241.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

new parameters:
quiet time(hrs) = 1.00

setup time(hrs)	=	2.00
luminosity lifetime(hrs)	=	17.3
pbar yield into Accumulator (ppm)	=	10.0
protons on target per cycle(x10**12)	=	1.80
kilocycles per hour	=	1.80
stacking efficiency	=	0.850
protons per bunch at low beta (x10**10)	=	7.00
Tev inj to low beta transfer efficiency	=	0.950
low beta (m)	=	0.500
overall emittance dilution (p)	=	0.100E-01
overall emittance dilution (pbar)	=	4.00
operational efficiency	=	0.600
longitudinal emittance per bunch	=	1.25
stack maximum	=	100.

STACK FOR THE OPTIMUM TIME

epslng/bunch	fraction	lumin/wk (pb)**-1	lumin(peak) 10**29	t stack hrs	stack size x10**10	dpbar(core) x10**10	pbar/bunch x10**10	emittance p mm-mrad	pb mm-mrad	trans eff	bb del-nu
1.200	0.652	1.082	56.408	20.025	74.700	48.708	5.990	15.010	13.415	0.738	0.007
1.250	0.664	1.094	57.369	20.330	74.600	49.505	6.090	15.010	13.405	0.738	0.007
1.300	0.674	1.105	58.235	20.602	74.500	50.219	6.180	15.010	13.395	0.738	0.007

log derivatives of integrated luminosity

quiet time(hrs)	=	1.00	log derivative = -0.191E-01
setup time(hrs)	=	2.00	log derivative = -0.858E-01
luminosity lifetime(hrs)	=	17.3	log derivative = 0.494
pbar yield into Accumulator (ppm)	=	10.0	log derivative = 0.000E+00
protons on target per cycle(x10**12)	=	1.80	log derivative = 0.000E+00
kilocycles per hour	=	1.80	log derivative = 0.000E+00
stacking efficiency	=	0.850	log derivative = 0.389
protons per bunch at low beta (x10**10)	=	7.00	log derivative = 1.00
Tev inj to low beta transfer efficiency	=	0.950	log derivative = 1.00
low beta (m)	=	0.500	log derivative = -1.01
overall emittance dilution (p)	=	0.100E-01	log derivative = -0.353E-03
overall emittance dilution (pbar)	=	4.00	log derivative = -0.141
operational efficiency	=	0.600	log derivative = 1.00
longitudinal emittance per bunch	=	1.25	log derivative = 0.263
stack maximum	=	100.	log derivative = 0.000E+00

sim results
For 100 stores
probability of a store failure = 0.550
Down time after a failure (hr) = 6.000
Mean time between failures (hr) = 9.500
Initial stack size (10**10) = 12.000
average luminoisity (pb**-1/week) = 1.201
average stack size = (10**10) 54.930
average store duration (hr) = 15.308
fractional downtime = 0.150
fraction of time in storage = 0.710

STACK TO NSMAX

epslng/bunch	fraction	lumin/day (nb)**-1	lumin(peak) 10**29	t stack hrs	stack size x10**10	dpbar(core) x10**10	pbar/bunch x10**10	emittance p mm-mrad	pb mm-mrad	trans eff	bb del-nu
1.200	0.622	1.122	61.453	22.589	100.000	62.211	7.101	15.010	15.920	0.685	0.007
1.250	0.635	1.135	62.722	23.056	100.000	63.495	7.248	15.010	15.920	0.685	0.007
1.300	0.647	1.147	63.891	23.485	100.000	64.679	7.383	15.010	15.920	0.685	0.007

log derivatives of integrated luminosity

quiet time(hrs)	=	1.00	log derivative = -0.192E-01
setup time(hrs)	=	2.00	log derivative = -0.768E-01

luminosity lifetime(hrs)	=	17.3	log derivative =	0.541
pbar yield into Accumulator (ppm)	=	10.0	log derivative =	0.000E+00
protons on target per cycle(x10**12)	=	1.80	log derivative =	0.000E+00
kilocycles per hour	=	1.80	log derivative =	0.000E+00
stacking efficiency	=	0.850	log derivative =	0.445
protons per bunch at low beta (x10**10)	=	7.00	log derivative =	1.00
Tev inj to low beta transfer efficiency	=	0.950	log derivative =	1.00
low beta (m)	=	0.500	log derivative =	-1.01
overall emittance dilution (p)	=	0.100E-01	log derivative =	-0.323E-03
overall emittance dilution (pbar)	=	4.00	log derivative =	-0.129
operational efficiency	=	0.600	log derivative =	1.00
longitudinal emittance per bunch	=	1.25	log derivative =	0.273
stack maximum	=	100.	log derivative =	-0.138

AVERAGE LUMINOSITY ESTIMATE

1993 RUN (Linac upgrade)

date = 29-AUG-91 time = 17:36:01

number of bunches= 6 peak stacking rate (ma/hr)= 5.400
number of crossings= 2
beam energy = 900.000 GeV
vary longitudinal emittance per bunch by +/- 0.050ev-sec

unstacking efficiency= 0.750
MR 20 GeV to Tev 150 GeV efficiency= (%) 92.000

parameters for transfer efficiency, Acc to MR at 20 GeV
0.1190000E+03-0.4661000E+01 0.1050000E+00

parameters for pbar emittance vs. stack size
0.2010000E+01 0.9920000E-01-0.1000000E-05

parameters for pbar longitudinal density vs.
stack size
0.5438000E+00 0.2010000E+00-0.5456000E-03

stacking rate vs intensity:
tevatron upgrade phase Ia

stack rate rolloff from a model
emittance scale factor= 1.500
stack rate into the Accumulator= 3.060 ma/hr
yield into the Accumulator= 10.000ppm
beam lifetime in model (hrs)= 300.000
table describing yield rolloff vs stack
entries= 250

stack	yield into the core									
1.000	9.945	9.922	9.899	9.876	9.852	9.827	9.802	9.777	9.752	9.726
11.000	9.700	9.674	9.648	9.622	9.596	9.569	9.543	9.517	9.490	9.464
21.000	9.437	9.411	9.385	9.359	9.333	9.308	9.282	9.257	9.232	9.207
31.000	9.182	9.157	9.133	9.109	9.086	9.062	9.039	9.016	8.993	8.971
41.000	8.949	8.927	8.905	8.884	8.863	8.842	8.822	8.801	8.781	8.761
51.000	8.742	8.722	8.703	8.684	8.665	8.646	8.628	8.609	8.591	8.572
61.000	8.554	8.536	8.518	8.499	8.481	8.462	8.444	8.425	8.406	8.387
71.000	8.368	8.349	8.329	8.309	8.288	8.267	8.246	8.224	8.201	8.178
81.000	8.155	8.131	8.106	8.080	8.053	8.026	7.998	7.969	7.938	7.907
91.000	7.875	7.841	7.807	7.770	7.733	7.694	7.654	7.612	7.569	7.524
101.000	7.478	7.429	7.379	7.327	7.272	7.216	7.158	7.097	7.034	6.969
111.000	6.902	6.832	6.759	6.683	6.605	6.524	6.441	6.354	6.264	6.171
121.000	6.075	5.975	5.872	5.766	5.655	5.542	5.424	5.303	5.177	5.047
131.000	4.914	4.776	4.633	4.486	4.335	4.179	4.018	3.852	3.681	3.505
141.000	3.324	3.138	2.946	2.749	2.545	2.336	2.122	1.901	1.674	1.441
151.000	1.201	0.955	0.703	0.443	0.177	0.000	0.000	0.000	0.000	0.000
161.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
171.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
181.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
191.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
201.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
211.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
221.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
231.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
241.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

new parameters:
quiet time(hrs) = 1.00

setup time(hrs)	=	2.00
luminosity lifetime(hrs)	=	15.1
pbar yield into Accumulator (ppm)	=	10.0
protons on target per cycle(x10**12)	=	3.00
kilocycles per hour	=	1.80
stacking efficiency	=	0.850
protons per bunch at low beta (x10**10)	=	10.0
Tev inj to low beta transfer efficiency	=	0.950
low beta (m)	=	0.500
overall emittance dilution (p)	=	0.100E-01
overall emittance dilution (pbar)	=	4.00
operational efficiency	=	0.600
longitudinal emittance per bunch	=	1.25
stack maximum	=	200.

STACK FOR THE OPTIMUM TIME

epslng/bunch	fraction	lumin/wk (pb)**-1	lumin(peak) 10**29	t stack hrs	stack size x10**10	dpbar(core) x10**10	pbar/bunch x10**10	emittance p mm-mrad	emittance pb mm-mrad	trans eff	bb del-nu
1.200	0.631	1.753	86.260	13.926	92.600	58.457	6.812	15.010	15.187	0.699	0.010
1.250	0.644	1.779	87.965	14.191	92.600	59.612	6.947	15.010	15.187	0.699	0.010
1.300	0.655	1.801	89.581	14.463	92.800	60.782	7.079	15.010	15.207	0.699	0.010

log derivatives of integrated luminosity

quiet time(hrs)	=	1.00	log derivative = -0.200E-01
setup time(hrs)	=	2.00	log derivative = -0.116
luminosity lifetime(hrs)	=	15.1	log derivative = 0.422
pbar yield into Accumulator (ppm)	=	10.0	log derivative = 0.000E+00
protons on target per cycle(x10**12)	=	3.00	log derivative = 0.000E+00
kilocycles per hour	=	1.80	log derivative = 0.000E+00
stacking efficiency	=	0.850	log derivative = 0.285
protons per bunch at low beta (x10**10)	=	10.0	log derivative = 1.00
Tev inj to low beta transfer efficiency	=	0.950	log derivative = 1.00
low beta (m)	=	0.500	log derivative = -1.01
overall emittance dilution (p)	=	0.100E-01	log derivative = -0.331E-03
overall emittance dilution (pbar)	=	4.00	log derivative = -0.132
operational efficiency	=	0.600	log derivative = 1.00
longitudinal emittance per bunch	=	1.25	log derivative = 0.340
stack maximum	=	200.	log derivative = 0.000E+00

sim results

For 100 stores

probability of a store failure =	0.550
Down time after a failure (hr) =	6.000
Mean time between failures (hr) =	9.500
Initial stack size (10**10) =	12.000
average luminoisity (pb**-1/week) =	1.920
average stack size = (10**10)	75.584
average store duration (hr) =	11.882
fractional downtime =	0.179
fraction of time in storage =	0.656

STACK TO NSMAX

epslng/bunch	fraction	lumin/day (nb)**-1	lumin(peak) 10**29	t stack hrs	stack size x10**10	dpbar(core) x10**10	pbar/bunch x10**10	emittance p mm-mrad	emittance pb mm-mrad	trans eff	bb del-nu
1.200	0.458	1.506	84.029	19.938	200.000	91.515	8.970	15.010	25.810	0.588	0.010
1.250	0.472	1.533	86.708	20.573	200.000	94.431	9.256	15.010	25.810	0.588	0.010
1.300	0.486	1.558	89.301	21.189	200.000	97.256	9.533	15.010	25.810	0.588	0.010

log derivatives of integrated luminosity

quiet time(hrs)	=	1.00	log derivative = -0.216E-01
setup time(hrs)	=	2.00	log derivative = -0.848E-01

luminosity lifetime(hrs)	=	15.1	log derivative =	0.551
pbar yield into Accumulator (ppm)	=	10.0	log derivative =	0.000E+00
protons on target per cycle(x10**12)	=	3.00	log derivative =	0.000E+00
kilocycles per hour	=	1.80	log derivative =	0.000E+00
stacking efficiency	=	0.850	log derivative =	0.445
protons per bunch at low beta (x10**10)	=	10.0	log derivative =	1.00
Tev inj to low beta transfer efficiency	=	0.950	log derivative =	1.00
low beta (m)	=	0.500	log derivative =	-1.01
overall emittance dilution (p)	=	0.100E-01	log derivative =	-0.245E-03
overall emittance dilution (pbar)	=	4.00	log derivative =	-0.980E-01
operational efficiency	=	0.600	log derivative =	1.00
longitudinal emittance per bunch	=	1.25	log derivative =	0.425
stack maximum	=	200.	log derivative =	-0.373

AVERAGE LUMINOSITY ESTIMATE

1994-5 RUN (Energy upgrade, multibunch)

date = 29-AUG-91 time = 17:36:51

number of bunches= 36 peak stacking rate (ma/hr)= 7.560
number of crossings= 2
beam energy = 1000.000 GeV
vary longitudinal emittance per bunch by +/- 0.050ev-sec

unstacking efficiency= 0.750
MR 20 GeV to Tev 150 GeV efficiency= (%) 92.000

parameters for transfer efficiency, Acc to MR at 20 GeV
0.1190000E+03-0.4661000E+01 0.1050000E+00

parameters for pbar emittance vs. stack size
0.2010000E+01 0.9920000E-01-0.1000000E-05

parameters for pbar longitudinal density vs.
stack size
0.5438000E+00 0.2010000E+00-0.5456000E-03

stacking rate vs intensity:
TEVATRON UPGRADE PHASE IB

stack rate rolloff from a model
emittance scale factor= 1.500
stack rate into the Accumulator= 7.560 ma/hr
yield into the Accumulator= 14.000ppm
beam lifetime in model (hrs)= 300.000
table describing yield rolloff vs stack
entries= 250

stack	yield into the core									
1.000	13.969	13.956	13.943	13.930	13.916	13.902	13.888	13.874	13.859	13.845
11.000	13.830	13.816	13.801	13.786	13.771	13.756	13.741	13.726	13.711	13.696
21.000	13.681	13.666	13.652	13.637	13.622	13.608	13.593	13.579	13.565	13.550
31.000	13.536	13.523	13.509	13.495	13.482	13.469	13.455	13.442	13.429	13.417
41.000	13.404	13.392	13.380	13.368	13.356	13.344	13.332	13.321	13.309	13.298
51.000	13.287	13.276	13.265	13.254	13.244	13.233	13.222	13.212	13.201	13.191
61.000	13.181	13.170	13.160	13.150	13.139	13.129	13.118	13.108	13.097	13.086
71.000	13.075	13.064	13.053	13.041	13.030	13.018	13.006	12.993	12.981	12.968
81.000	12.954	12.941	12.927	12.912	12.897	12.881	12.865	12.849	12.832	12.814
91.000	12.796	12.777	12.757	12.737	12.715	12.693	12.671	12.647	12.623	12.597
101.000	12.571	12.543	12.515	12.485	12.454	12.422	12.389	12.355	12.319	12.283
111.000	12.244	12.205	12.163	12.121	12.076	12.031	11.983	11.934	11.883	11.830
121.000	11.776	11.719	11.661	11.601	11.538	11.474	11.407	11.338	11.267	11.194
131.000	11.118	11.040	10.959	10.876	10.790	10.701	10.610	10.516	10.419	10.320
141.000	10.217	10.111	10.003	9.891	9.776	9.657	9.536	9.411	9.282	9.150
151.000	9.014	8.875	8.731	8.584	8.434	8.279	8.120	7.957	7.790	7.618
161.000	7.443	7.262	7.078	6.889	6.695	6.496	6.293	6.085	5.872	5.654
171.000	5.430	5.202	4.968	4.729	4.485	4.235	3.979	3.718	3.450	3.177
181.000	2.898	2.613	2.322	2.025	1.721	1.411	1.095	0.771	0.442	0.105
191.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
201.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
211.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
221.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
231.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
241.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

new parameters:
quiet time(hrs) = 1.00

setup time(hrs)	=	2.00
luminosity lifetime(hrs)	=	21.7
pbar yield into Accumulator (ppm)	=	14.0
protons on target per cycle(x10**12)	=	3.00
kilocycles per hour	=	1.80
stacking efficiency	=	0.850
protons per bunch at low beta (x10**10)	=	10.0
Tev inj to low beta transfer efficiency	=	0.950
low beta (m)	=	0.500
overall emittance dilution (p)	=	0.100E-01
overall emittance dilution (pbar)	=	4.00
operational efficiency	=	0.600
longitudinal emittance per bunch	=	0.500
stack maximum	=	200.

STACK FOR THE OPTIMUM TIME

epslng/bunch	fraction	lumin/wk (pb)**-1	lumin(peak) 10**29	t stack hrs	stack size x10**10	dpbar(core) x10**10	pbar/bunch x10**10	emittance p mm-mrad	emittance pb mm-mrad	trans eff	bb del-nu
0.450	0.744	2.881	130.651	17.443	135.700	100.978	1.766	15.010	19.453	0.630	0.010
0.500	0.747	2.892	131.744	17.762	137.200	102.557	1.789	15.010	19.601	0.628	0.010
0.550	0.749	2.897	132.344	17.962	138.200	103.515	1.802	15.010	19.700	0.627	0.010

log derivatives of integrated luminosity

quiet time(hrs)	=	1.00	log derivative = -0.146E-01
setup time(hrs)	=	2.00	log derivative = -0.963E-01
luminosity lifetime(hrs)	=	21.7	log derivative = 0.372
pbar yield into Accumulator (ppm)	=	14.0	log derivative = 0.000E+00
protons on target per cycle(x10**12)	=	3.00	log derivative = 0.000E+00
kilocycles per hour	=	1.80	log derivative = 0.000E+00
stacking efficiency	=	0.850	log derivative = 0.261
protons per bunch at low beta (x10**10)	=	10.0	log derivative = 1.00
Tev inj to low beta transfer efficiency	=	0.950	log derivative = 1.00
low beta (m)	=	0.500	log derivative = -1.01
overall emittance dilution (p)	=	0.100E-01	log derivative = -0.289E-03
overall emittance dilution (pbar)	=	4.00	log derivative = -0.116
operational efficiency	=	0.600	log derivative = 1.00
longitudinal emittance per bunch	=	0.500	log derivative = 0.265E-01
stack maximum	=	200.	log derivative = 0.000E+00

sim results
For 100 stores
probability of a store failure = 0.550
Down time after a failure (hr) = 6.000
Mean time between failures (hr) = 9.500
Initial stack size (10**10) = 12.000
average luminoisity (pb**-1/week) = 2.822
average stack size = (10**10) 97.112
average store duration (hr) = 13.126
fractional downtime = 0.200
fraction of time in storage = 0.652

STACK TO NSMAX

epslng/bunch	fraction	lumin/day (nb)**-1	lumin(peak) 10**29	t stack hrs	stack size x10**10	dpbar(core) x10**10	pbar/bunch x10**10	emittance p mm-mrad	emittance pb mm-mrad	trans eff	bb del-nu
0.450	0.710	2.978	144.916	22.104	200.000	142.043	2.320	15.010	25.810	0.588	0.010
0.500	0.726	3.022	148.199	22.605	200.000	145.261	2.373	15.010	25.810	0.588	0.010
0.550	0.736	3.049	150.271	22.921	200.000	147.291	2.406	15.010	25.810	0.588	0.010

log derivatives of integrated luminosity

quiet time(hrs)	=	1.00	log derivative = -0.156E-01
setup time(hrs)	=	2.00	log derivative = -0.781E-01

luminosity lifetime(hrs)	=	21.7	log derivative =	Ø.449
pbar yield into Accumulator (ppm)	=	14.Ø	log derivative =	Ø.ØØØE+ØØ
protons on target per cycle(x1Ø**12)	=	3.ØØ	log derivative =	Ø.ØØØE+ØØ
kilocycles per hour	=	1.8Ø	log derivative =	Ø.ØØØE+ØØ
stacking efficiency	=	Ø.85Ø	log derivative =	Ø.356
protons per bunch at low beta (x1Ø**1Ø)	=	1Ø.Ø	log derivative =	1.ØØ
Tev inj to low beta transfer efficiency	=	Ø.95Ø	log derivative =	1.ØØ
low beta (m)	=	Ø.5ØØ	log derivative =	-1.Ø1
overall emittance dilution (p)	=	Ø.1ØØE-Ø1	log derivative =	-Ø.245E-Ø3
overall emittance dilution (pbar)	=	4.ØØ	log derivative =	-Ø.98ØE-Ø1
operational efficiency	=	Ø.6ØØ	log derivative =	1.ØØ
longitudinal emittance per bunch	=	Ø.5ØØ	log derivative =	Ø.117
stack maximum	=	2ØØ.	log derivative =	Ø.3Ø2E-Ø1

AVERAGE LUMINOSITY ESTIMATE

1996 RUN (Main Injector)

date = 29-AUG-91 time = 17:37:53

number of bunches= 36 peak stacking rate (ma/hr)= 16.800
number of crossings= 2
beam energy = 1000.000 GeV
vary longitudinal emittance per bunch by +/- 0.050ev-sec

unstacking efficiency= 0.750
MR 20 GeV to Tev 150 GeV efficiency= (%) 92.000

parameters for transfer efficiency, Acc to MR at 20 GeV
0.1000000E+03 0.0000000E+00 0.0000000E+00

parameters for pbar emittance vs. stack size
0.2010000E+01 0.9920000E-01-0.1000000E-05

parameters for pbar longitudinal density vs.
stack size
0.5438000E+00 0.2010000E+00-0.5456000E-03

stacking rate vs intensity:
MAIN INJECTOR : PHASE IIa

stack rate rolloff from a model
emittance scale factor= 1.500
stack rate into the Accumulator= 16.800 ma/hr
yield into the Accumulator= 14.000ppm
beam lifetime in model (hrs)= 300.000
table describing yield rolloff vs stack
entries= 250

stack	yield into the core									
1.000	13.986	13.980	13.974	13.968	13.962	13.956	13.950	13.943	13.937	13.930
11.000	13.924	13.917	13.910	13.904	13.897	13.890	13.883	13.877	13.870	13.863
21.000	13.857	13.850	13.843	13.837	13.830	13.823	13.817	13.810	13.804	13.798
31.000	13.791	13.785	13.779	13.773	13.767	13.761	13.755	13.749	13.743	13.738
41.000	13.732	13.726	13.721	13.715	13.710	13.705	13.700	13.694	13.689	13.684
51.000	13.679	13.674	13.669	13.664	13.660	13.655	13.650	13.645	13.641	13.636
61.000	13.631	13.627	13.622	13.617	13.613	13.608	13.603	13.598	13.594	13.589
71.000	13.584	13.579	13.574	13.569	13.563	13.558	13.553	13.547	13.541	13.535
81.000	13.529	13.523	13.517	13.510	13.504	13.497	13.489	13.482	13.474	13.466
91.000	13.458	13.450	13.441	13.431	13.422	13.412	13.402	13.391	13.380	13.369
101.000	13.357	13.344	13.332	13.318	13.304	13.290	13.275	13.260	13.244	13.227
111.000	13.210	13.192	13.174	13.154	13.134	13.114	13.092	13.070	13.047	13.024
121.000	12.999	12.974	12.947	12.920	12.892	12.863	12.833	12.802	12.770	12.737
131.000	12.703	12.668	12.632	12.594	12.555	12.516	12.475	12.432	12.389	12.344
141.000	12.298	12.250	12.201	12.151	12.099	12.046	11.991	11.935	11.877	11.817
151.000	11.756	11.694	11.629	11.563	11.495	11.425	11.354	11.281	11.205	11.128
161.000	11.049	10.968	10.885	10.800	10.713	10.623	10.532	10.438	10.342	10.244
171.000	10.144	10.041	9.936	9.828	9.718	9.606	9.491	9.373	9.253	9.130
181.000	9.004	8.876	8.745	8.611	8.475	8.335	8.193	8.047	7.899	7.747
191.000	7.593	7.435	7.274	7.110	6.943	6.772	6.598	6.420	6.239	6.055
201.000	5.867	5.676	5.480	5.282	5.079	4.873	4.663	4.449	4.231	4.009
211.000	3.783	3.553	3.319	3.081	2.838	2.592	2.341	2.085	1.826	1.561
221.000	1.293	1.019	0.741	0.459	0.171	0.000	0.000	0.000	0.000	0.000
231.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
241.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

new parameters:
quiet time(hrs) = 1.00

```
setup time(hrs)                               =   2.00
luminosity lifetime(hrs)                      =   16.2
pbar yield into Accumulator (ppm)             =   14.0
protons on target per cycle(x10**12)          =   5.00
kilocycles per hour                           =   2.40
stacking efficiency                           =  0.850
protons per bunch at low beta (x10**10)       =   33.0
Tev inj to low beta transfer efficiency       =  0.950
low beta (m)                                  =  0.500
overall emittance dilution (p)                =   15.0
overall emittance dilution (pbar)             =  0.100E-01
operational efficiency                        =  0.600
longitudinal emittance per bunch              =  0.500
stack maximum                                 =   200.
```

STACK FOR THE OPTIMUM TIME

epslng/bunch	fraction	lumin/wk (pb)**-1	lumin(peak) 10**29	t stack hrs	stack size x10**10	dpbar(core) x10**10	pbar/bunch x10**10	emittance p mm-mrad	pb mm-mrad	trans eff	bb del-nu
0.450	0.713	12.061	557.099	11.929	197.400	140.648	3.415	30.000	21.563	0.874	0.016
0.500	0.727	12.282	571.880	12.412	199.500	144.961	3.519	30.000	21.771	0.874	0.016
0.550	0.736	12.423	582.111	12.778	201.100	148.005	3.593	30.000	21.929	0.874	0.016

```
log derivatives of integrated luminosity
quiet time(hrs)                               =   1.00      log derivative = -0.170E-01
setup time(hrs)                               =   2.00      log derivative = -0.130
luminosity lifetime(hrs)                      =   16.2      log derivative =  0.359
pbar yield into Accumulator (ppm)             =   14.0      log derivative =  0.000E+00
protons on target per cycle(x10**12)          =   5.00      log derivative =  0.000E+00
kilocycles per hour                           =   2.40      log derivative =  0.000E+00
stacking efficiency                           =  0.850      log derivative =  0.213
protons per bunch at low beta (x10**10)       =   33.0      log derivative =   1.00
Tev inj to low beta transfer efficiency       =  0.950      log derivative =   1.00
low beta (m)                                  =  0.500      log derivative =  -1.01
overall emittance dilution (p)                =   15.0      log derivative = -0.290
overall emittance dilution (pbar)             =  0.100E-01  log derivative = -0.193E-03
operational efficiency                        =  0.600      log derivative =   1.00
longitudinal emittance per bunch              =  0.500      log derivative =  0.147
stack maximum                                 =   200.      log derivative =  0.000E+00
```

```
sim results
For   100 stores
probability of a store failure =      0.550
Down time after a failure (hr) =      6.000
Mean time between failures (hr) =      9.500
Initial stack size (10**10) =      12.000
average luminoisity ( pb**-1/week) =     12.432
average stack size = (10**10)    159.693
average store duration (hr) =     10.337
fractional downtime =       0.204
fraction of time in storage =      0.617
```

STACK TO NSMAX

epslng/bunch	fraction	lumin/day (nb)**-1	lumin(peak) 10**29	t stack hrs	stack size x10**10	dpbar(core) x10**10	pbar/bunch x10**10	emittance p mm-mrad	pb mm-mrad	trans eff	bb del-nu
0.450	0.710	12.487	559.834	9.947	200.000	142.043	3.448	30.000	21.820	0.874	0.016
0.500	0.726	12.731	572.516	10.172	200.000	145.261	3.527	30.000	21.820	0.874	0.016
0.550	0.736	12.883	580.520	10.315	200.000	147.291	3.576	30.000	21.820	0.874	0.016

```
log derivatives of integrated luminosity
quiet time(hrs)                               =   1.00      log derivative = -0.138E-01
setup time(hrs)                               =   2.00      log derivative = -0.152
```

luminosity lifetime(hrs)	= 16.2	log derivative = 0.307
pbar yield into Accumulator (ppm)	= 14.0	log derivative = 0.000E+00
protons on target per cycle(x10**12)	= 5.00	log derivative = 0.000E+00
kilocycles per hour	= 2.40	log derivative = 0.000E+00
stacking efficiency	= 0.850	log derivative = 0.142
protons per bunch at low beta (x10**10)	= 33.0	log derivative = 1.00
Tev inj to low beta transfer efficiency	= 0.950	log derivative = 1.00
low beta (m)	= 0.500	log derivative = -1.01
overall emittance dilution (p)	= 15.0	log derivative = -0.290
overall emittance dilution (pbar)	= 0.100E-01	log derivative = -0.192E-03
operational efficiency	= 0.600	log derivative = 1.00
longitudinal emittance per bunch	= 0.500	log derivative = 0.156
stack maximum	= 200.	log derivative = 0.331

AVERAGE LUMINOSITY ESTIMATE

1997 RUN (Main Injector, 2-4 GHz pbar stack tail)

date = 29-AUG-91 time = 17:39:19

number of bunches= 36 peak stacking rate (ma/hr)= 16.800
number of crossings= 2
beam energy = 1000.000 GeV
vary longitudinal emittance per bunch by +/- 0.050ev-sec

unstacking efficiency= 0.750
MR 20 GeV to Tev 150 GeV efficiency= (%) 92.000

parameters for transfer efficiency, Acc to MR at 20 GeV
0.1000000E+03 0.0000000E+00 0.0000000E+00

parameters for pbar emittance vs. stack size
0.2010000E+01 0.9920000E-01-0.1000000E-05

parameters for pbar longitudinal density vs.
stack size
0.5438000E+00 0.2010000E+00-0.5456000E-03

stacking rate vs intensity:
Upgrade with MI, 2-4 GHZ stack tail

stack rate rolloff from a model
emittance scale factor= 1.500
stack rate into the Accumulator= 16.800 ma/hr
yield into the Accumulator= 14.000ppm
beam lifetime in model (hrs)= 300.000
table describing yield rolloff vs stack
entries= 400

stack	yield into the core									
1.000	13.830	13.826	13.822	13.818	13.814	13.810	13.806	13.802	13.799	13.795
11.000	13.792	13.789	13.785	13.782	13.779	13.776	13.773	13.770	13.768	13.765
21.000	13.762	13.759	13.757	13.754	13.752	13.750	13.747	13.745	13.743	13.740
31.000	13.738	13.736	13.734	13.732	13.729	13.727	13.725	13.723	13.721	13.719
41.000	13.717	13.715	13.713	13.711	13.709	13.707	13.705	13.703	13.701	13.699
51.000	13.697	13.695	13.693	13.691	13.689	13.687	13.685	13.683	13.681	13.678
61.000	13.676	13.674	13.672	13.669	13.667	13.664	13.662	13.659	13.657	13.654
71.000	13.652	13.649	13.646	13.643	13.640	13.637	13.634	13.631	13.628	13.625
81.000	13.622	13.618	13.615	13.611	13.608	13.604	13.601	13.597	13.593	13.589
91.000	13.585	13.581	13.576	13.572	13.568	13.563	13.558	13.554	13.549	13.544
101.000	13.539	13.534	13.528	13.523	13.518	13.512	13.506	13.501	13.495	13.489
111.000	13.482	13.476	13.470	13.463	13.457	13.450	13.443	13.436	13.429	13.422
121.000	13.414	13.407	13.399	13.391	13.383	13.375	13.367	13.358	13.350	13.341
131.000	13.333	13.324	13.315	13.305	13.296	13.286	13.277	13.267	13.257	13.247
141.000	13.236	13.226	13.215	13.205	13.194	13.183	13.171	13.160	13.148	13.137
151.000	13.125	13.113	13.100	13.088	13.075	13.063	13.050	13.036	13.023	13.010
161.000	12.996	12.982	12.968	12.954	12.940	12.925	12.910	12.896	12.880	12.865
171.000	12.850	12.834	12.818	12.802	12.786	12.769	12.753	12.736	12.719	12.702
181.000	12.684	12.667	12.649	12.631	12.613	12.594	12.575	12.557	12.538	12.518
191.000	12.499	12.479	12.459	12.439	12.419	12.398	12.377	12.356	12.335	12.313
201.000	12.292	12.270	12.248	12.225	12.202	12.180	12.156	12.133	12.109	12.086
211.000	12.061	12.037	12.013	11.988	11.963	11.937	11.912	11.886	11.859	11.833
221.000	11.806	11.779	11.752	11.725	11.697	11.669	11.640	11.612	11.583	11.553
231.000	11.524	11.494	11.464	11.434	11.403	11.372	11.340	11.309	11.277	11.244
241.000	11.212	11.179	11.145	11.112	11.078	11.043	11.009	10.974	10.938	10.902
251.000	10.866	10.830	10.793	10.756	10.718	10.680	10.642	10.603	10.564	10.524
261.000	10.484	10.444	10.403	10.362	10.320	10.278	10.236	10.193	10.150	10.106
271.000	10.062	10.017	9.972	9.926	9.880	9.834	9.787	9.739	9.691	9.643

281.000	9.594	9.544	9.494	9.444	9.393	9.341	9.289	9.237	9.184	9.130
291.000	9.076	9.021	8.966	8.910	8.853	8.796	8.739	8.680	8.622	8.562
301.000	8.502	8.441	8.380	8.318	8.256	8.193	8.129	8.064	7.999	7.933
311.000	7.867	7.800	7.732	7.664	7.594	7.524	7.454	7.383	7.311	7.238
321.000	7.164	7.090	7.015	6.939	6.863	6.785	6.707	6.629	6.549	6.468
331.000	6.387	6.305	6.222	6.138	6.054	5.968	5.882	5.795	5.707	5.618
341.000	5.528	5.438	5.346	5.254	5.160	5.066	4.971	4.874	4.777	4.679
351.000	4.580	4.480	4.379	4.277	4.173	4.069	3.964	3.858	3.751	3.642
361.000	3.533	3.422	3.311	3.198	3.084	2.969	2.853	2.736	2.618	2.498
371.000	2.377	2.255	2.132	2.008	1.882	1.755	1.627	1.498	1.367	1.235
381.000	1.102	0.967	0.831	0.694	0.555	0.415	0.273	0.130	0.000	0.000
391.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

new parameters:

quiet time(hrs)	=	1.00
setup time(hrs)	=	2.00
luminosity lifetime(hrs)	=	19.0
pbar yield into Accumulator (ppm)	=	14.0
protons on target per cycle(x10**12)	=	5.00
kilocycles per hour	=	2.40
stacking efficiency	=	0.850
protons per bunch at low beta (x10**10)	=	33.0
Tev inj to low beta transfer efficiency	=	0.950
low beta (m)	=	0.500
overall emittance dilution (p)	=	15.0
overall emittance dilution (pbar)	=	0.100E-01
operational efficiency	=	0.600
longitudinal emittance per bunch	=	0.500
stack maximum	=	200.

STACK FOR THE OPTIMUM TIME

epslng/bunch	fraction	lumin/wk (pb)**-1	lumin(peak) 10**29	t stack hrs	stack x10**10	size dpbar(core) x10**10	pbar/bunch x10**10	emittance p mm-mrad	pb mm-mrad	trans eff	bb del-nu
0.450	0.662	13.357	591.537	12.640	247.000	163.530	3.970	30.000	26.461	0.874	0.016
0.500	0.679	13.818	620.632	13.624	257.100	174.602	4.239	30.000	27.458	0.874	0.016
0.550	0.694	14.183	645.536	14.504	265.600	184.259	4.473	30.000	28.297	0.874	0.016

log derivatives of integrated luminosity

quiet time(hrs)	=	1.00	log derivative = -0.147E-01
setup time(hrs)	=	2.00	log derivative = -0.120
luminosity lifetime(hrs)	=	19.0	log derivative = 0.338
pbar yield into Accumulator (ppm)	=	14.0	log derivative = 0.000E+00
protons on target per cycle(x10**12)	=	5.00	log derivative = 0.000E+00
kilocycles per hour	=	2.40	log derivative = 0.000E+00
stacking efficiency	=	0.850	log derivative = 0.203
protons per bunch at low beta (x10**10)	=	33.0	log derivative = 1.00
Tev inj to low beta transfer efficiency	=	0.950	log derivative = 1.00
low beta (m)	=	0.500	log derivative = -1.01
overall emittance dilution (p)	=	15.0	log derivative = -0.261
overall emittance dilution (pbar)	=	0.100E-01	log derivative = -0.174E-03
operational efficiency	=	0.600	log derivative = 1.00
longitudinal emittance per bunch	=	0.500	log derivative = 0.299
stack maximum	=	200.	log derivative = 0.000E+00

sim results
For 100 stores
probability of a store failure = 0.550
Down time after a failure (hr) = 6.000
Mean time between failures (hr) = 9.500
Initial stack size (10**10) = 12.000
average luminoisity (pb**-1/week) = 15.693
average stack size = (10**10) 228.680
average store duration (hr) = 12.662

fractional downtime = 0.155
fraction of time in storage = 0.683

STACK TO NSMAX

epslng/bunch	fraction	lumin/day (nb)**-1	lumin(peak) 10**29	t stack hrs	stack size x10**10	dpbar(core) x10**10	pbar/bunch x10**10	emittance p mm-mrad	emittance pb mm-mrad	trans eff	bb del-nu
0.450	0.710	13.057	559.834	9.947	200.000	142.043	3.448	30.000	21.820	0.874	0.016
0.500	0.726	13.322	572.516	10.172	200.000	145.261	3.527	30.000	21.820	0.874	0.016
0.550	0.736	13.489	580.520	10.315	200.000	147.291	3.576	30.000	21.820	0.874	0.016

log derivatives of integrated luminosity

quiet time(hrs)	= 1.00	log derivative = -0.102E-01
setup time(hrs)	= 2.00	log derivative = -0.152
luminosity lifetime(hrs)	= 19.0	log derivative = 0.267
pbar yield into Accumulator (ppm)	= 14.0	log derivative = 0.000E+00
protons on target per cycle(x10**12)	= 5.00	log derivative = 0.000E+00
kilocycles per hour	= 2.40	log derivative = 0.000E+00
stacking efficiency	= 0.850	log derivative = 0.105
protons per bunch at low beta (x10**10)	= 33.0	log derivative = 1.00
Tev inj to low beta transfer efficiency	= 0.950	log derivative = 1.00
low beta (m)	= 0.500	log derivative = -1.01
overall emittance dilution (p)	= 15.0	log derivative = -0.290
overall emittance dilution (pbar)	= 0.100E-01	log derivative = -0.193E-03
operational efficiency	= 0.600	log derivative = 1.00
longitudinal emittance per bunch	= 0.500	log derivative = 0.162
stack maximum	= 200.	log derivative = 0.361